# Life Cycle Assessment of Triticale (× *Triticosecale*):

## *a New Zealand 'Cradle to Farm Gate' assessment of net energy yield, global warming potential and eutrophication impacts of biomass crop production for bioenergy*

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Funded by the Biomass to Syngas to Liquid Biofuel project, Chemical and Process Engineering Department, University of Canterbury

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## Summary

The production of biofuels from crop biomass is one means to address two key issues: finite fossil fuel supply and environmental impacts of fossil fuel use on climate change through global warming. This Life Cycle Assessment (LCA) report is part of a New Zealand (NZ) biofuels research project at the University of Canterbury to advance biomass gasification and liquid fuel synthesis from the syngas. The aim is to characterise the most promising non-woody biomass species for use as gasification feedstock. The species reported here is triticale (× Triticosecale). It is a hybrid of rye and wheat bred for its grain but also having high biomass production in NZ, more than 22 tonnes dry mass per hectare (tDM/ha).

Our approach to assessing biomass species for gasification included: (1) writing a protocol for how to best grow each crop under NZ conditions, and (2) to do an LCA. The protocol characterises each biomass species for its ability to produce biomass, while the LCA quantifies environmental impacts and energy consumption from producing the biomass feedstock. The scope of this study is from Cradle to Farm Gate, not to the final production and use of fuel. LCA methodology was followed, with identified limitations and a modified presentation style. LCA practice recognises several environmental impact categories; this study quantified two factors of clear relevance, Global Warming Potential (GWP) and eutrophication (EUT). Energy consumption and net energy yield (gross energy stored in the biomass minus energy consumption to produce it) were also calculated, as they are of high relevance to a project designed to introduce a new fuel energy technology.

The main task was to develop a Life Cycle Inventory (LCI) containing the most appropriate inputs for calculating the impacts of each farming operation in triticale biomass production under NZ conditions. A spreadsheet approach was used for this. This alternative to the use of LCI databases was feasible given the practical decision to limit the LCA to two impact categories. The LCI was developed on per ha basis, since that is how farming inputs are quantified. The basic functional unit used to examine (and in the future to minimise) triticale production impacts on an area basis is: FU = *cultivation of one hectare of triticale shoot biomass.* The time basis (one year) is straightforward as triticale is an annual type crop.

The overall impacts were energy consumption of 15.2 GJ/ha-yr and GWP of 1905 kg $CO_2$e/ha-yr. Fertiliser use was the primary hotspot for both. Its energy consumption was 75% of the total. More of the impact on GWP was from the soil emissions of $N_2O$ and $CO_2$ (846 kg $CO_2$e/ha-yr from N fertiliser plus 218 kg $CO_2$e/ha-yr from lime) than fertiliser manufacture (522 kg $CO_2$e/ha-yr). Diesel fuel use to grow triticale, while greater than for the biomass species giant miscanthus (Mxg), was in terms of its triticale LCA impacts very

secondary to fertiliser for both energy consumption and GWP impact, so low in a relative sense.

EUT, which lowers the quality of waterways, is the second impact category studied (in units of phosphate equivalent and focusing on emissions from fertiliser and diesel fuel use). EUT impacts from N-containing emissions were largely from use of fertiliser nitrogen (2.34 kg PO4e/ha-yr), including a tiny amount (≈ 0.02%) of $N_2O$ from the use of diesel in tractors and trucks. The other EUT source is phosphorus (P) fertiliser, attached to soil that is eroded to waterways. The crop removal of P (36 kg/ha-yr) is about nine times higher than for Mxg. Typical P fertiliser use will have an impact on EUT of 0.92 kg PO4e/ha-yr. The overall EUT footprint from triticale cropping is 3.87 kg PO4e/ha-yr.

Net energy yield equals the gross energy yield (338.6 GJ/ha-yr) minus energy consumption (15.2 GJ/ha-yr) or 323.4 GJ/ha-yr. The energy ratio between gross yield and consumption is 22 to 1, reasonably good but lower than both of the other biomass species assessed. The calculated energy yield and energy ratio (which are area-based) will both vary with the value used for the DM yield/ha.

The footprint data for triticale and the other two biomass species are also calculated on per tonne basis. That is the basis that will be directly useful to future assessments of the conversion process of biomass to biofuel or bioenergy. It is likely that the use of biodiesel (produced from a ha of triticale biomass) in place of fossil diesel fuel in tractors or other engines will prove to have a large net benefit for GWP, but certainty of this must await an assessment of the GWP of the conversion process from biomass to biofuel.

# Life Cycle Assessment of Triticale (× *Triticosecale*): a New Zealand 'Cradle to Farm Gate' assessment of key environmental impacts and energy balance of biomass crop production for bioenergy

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# INTRODUCTION

Research to develop new transport fuels has two aims. The first is to address the issue of finite fossil fuel supply. Secondly, new biofuels should reduce the key environmental impact of fossil fuel use, climate change through global warming. To assess this however, it is also important to know what the environmental effects of each biofuel are. Life Cycle Assessment is the formal tool used to provide this information. To quote a recent LCA in New Zealand (McDevitt, 2011): “Life Cycle Assessment generally comprises four major components:

- Goal and Scope definition;
- Life Cycle Inventory (LCI) - data collection and calculation of an inventory of materials, energy and emissions related to the system being studied;
- Life Cycle Impact Assessment - analysis of data to evaluate contributions to various environmental impact categories; and
- Interpretation - where data are analysed in the context of the methodology, scope and study goals and where the quality of any study conclusions is assessed”.

While this structure was followed for this environmental assessment of triticale biomass production, this report is not intended to be a complete LCA document as prescribed by the body of New Zealand LCA professionals. Rather, it aims to serve the needs of a particular biofuels research project by the Chemical and Process Engineering Department of the University of Canterbury. The project is advancing the technology of biomass gasification and liquid fuel synthesis from the syngas and is named Biomass To Syngas to Liquids (BTSL).

One project aim of the BTSL programme is to characterise the best few non-woody biomass species for use as gasification plant feedstock. This research aspect has been provided by Rocky Renquist, the principal of Bioenergy Cropping Solutions, subcontracted to the University of Canterbury. The work was started within Plant & Food Research.

The findings from the Life Cycle Assessment analysis will be a valuable element in the overall project so that the environmental impacts of producing and using the end product biofuel are known and especially to quantify the energy balance of the overall process, since the underlying aim of the technology is to produce a new energy source for transport. Milestone 28 under Objective 4 of the U of C contract with MBIE reads: “Life cycle analysis is conducted to analyse the energy use and environmental impacts during biomass production and handling.”

Since the subcontract to complete the objective relating feedstock biomass production in now finished, while the engineering research will continue, the priority for the LCA work was to quantify impacts and energy use for the on-farm biomass cropping (Cradle to Farm Gate) phase. This enabled the LCA to be done incorporating the crop science expertise of Rocky Renquist, who had also developed a protocol for each of the three final species (among many species screened during the first two years), as specified in Milestone 28. The protocols described each species and detailed how it is best managed to produce biomass, based on NZ research findings and any relevant commercial experience; these protocols were used as the basis to identify the appropriate input factors to use in the LCA. The practical intent of using LCA is to quantify the potential of each species as a sustainable gasification feedstock and also enabling a comparison of the biomass species under NZ conditions

The species assessed in this LCA is triticale (×*Triticosecale*), using the whole above-ground plant mass rather than just the grain. Triticale is an annual type crop with demonstrated high biomass production.

# METHODS

Our New Zealand field trials with triticale were conducted during three years in the Southland region. The full details of these trials are described in the Triticale Protocol, a report from Bioenergy Cropping Solutions Ltd to the BTSL Project. Details most relevant to this LCA work are included here in the METHODS section of this report, while field trial findings are part of the RESULTS section of this LCA.

An LCA approach was applied to New Zealand cropping of three biomass species, meeting both time efficiency and reasonable accuracy requirements. Unlike the other two species, the agricultural inputs for triticale crop production were available under NZ conditions, as a cereal species used for making whole crop silage for dairy cows. Some of the key Life Cycle Inventory data relating cropping inputs to environmental impacts is also being developed in NZ, e.g., by Barber (2011a). Other LCI data that were identified as relevant by LCA professionals in NZ were gathered from overseas data sources (largely published in Europe). Some data were modified to suit NZ conditions. When European LCI data are directly applicable to NZ they are most efficiently accessed through LCA software designed for this purpose (Baumann & Tillman, 2004).

The other way to process and analyse these data is by constructing an operational calculation worksheet created for this purpose. This is the primary approach used in this analysis and was feasible due to the other practical decision to limit the LCA to a just a few environmental impact factors, as appropriate for the purpose and time resources available within the BTSL programme.

Since this project is designed to evaluate and introduce a new fuel energy technology potentially replacing current fossil fuels (diesel and petrol), energy consumption and energy balance were chosen as one very necessary focus of the LCA. The environmental impact factors quantified in this focused LCA were global warming potential (GWP) and eutrophication (EUT). Reducing GWP is the primary reason to replace fossil fuels and adverse agricultural impacts on the environment are most noticeable with regard to the pollution of surface and ground water, which is best assessed with EUT.

## Goal of the study

The goal of this LCA study is to assess the energy consumption, GWP and EUT impacts of the cultivation of whole crop triticale (×*Triticosecale*) in New Zealand. In this LCA, relevant data collection and calculation of an inventory of materials, energy and emissions related to the triticale farming system are presented.

The *functional unit* of the study is a measure that reflects and quantifies the function of a production system and allows the comparison with other systems. The main function of the triticale crop is to provide stored energy (in the standing biomass) in the form of feedstock that, once it leaves the farm-system boundary and is taken to an off-farm gasification plant, is used to produce syngas and (in another factory) liquid fuel from the syngas. However, during the farming of a crop the inputs are always applied on per ha basis, since yield is variable and not known in advance of farming operations. The inputs in the LCI data set need to be quantified and expressed on an area basis, therefore the appropriate functional unit for this LCA is *FU = cultivation of one hectare of triticale shoot biomass.* This will enable an area-based comparison (at the farm gate) among the three New Zealand-grown biomass species chosen as the best options to supply feedstock to a future gasification plant.

Finally, from the perspective of producing bioenergy from a range of crop species and also assessing the energy balance in producing biomass of each species, a different FU is required, because other biomass crops do not necessarily have the same dry mass yield per ha. Therefore, this analysis will also use a second functional unit: FU = *1.0 tonne dry mass of triticale (contained within biomass of known moisture content, at the farm gate)*. This is used to calculate energy costs and environmental footprints in relation to the biomass inputs and see the effect of different dry mass yields/ha. This will enable the use of the results in any future analysis covering the processing of biomass into biofuel. The target audience of the study will be the BTSL research project at the University of Canterbury that has contracted the work, and later the public readership of the reported findings of the overall BTSL project. This LCA is not intended to be used to support comparative assertions intended for public disclosure.

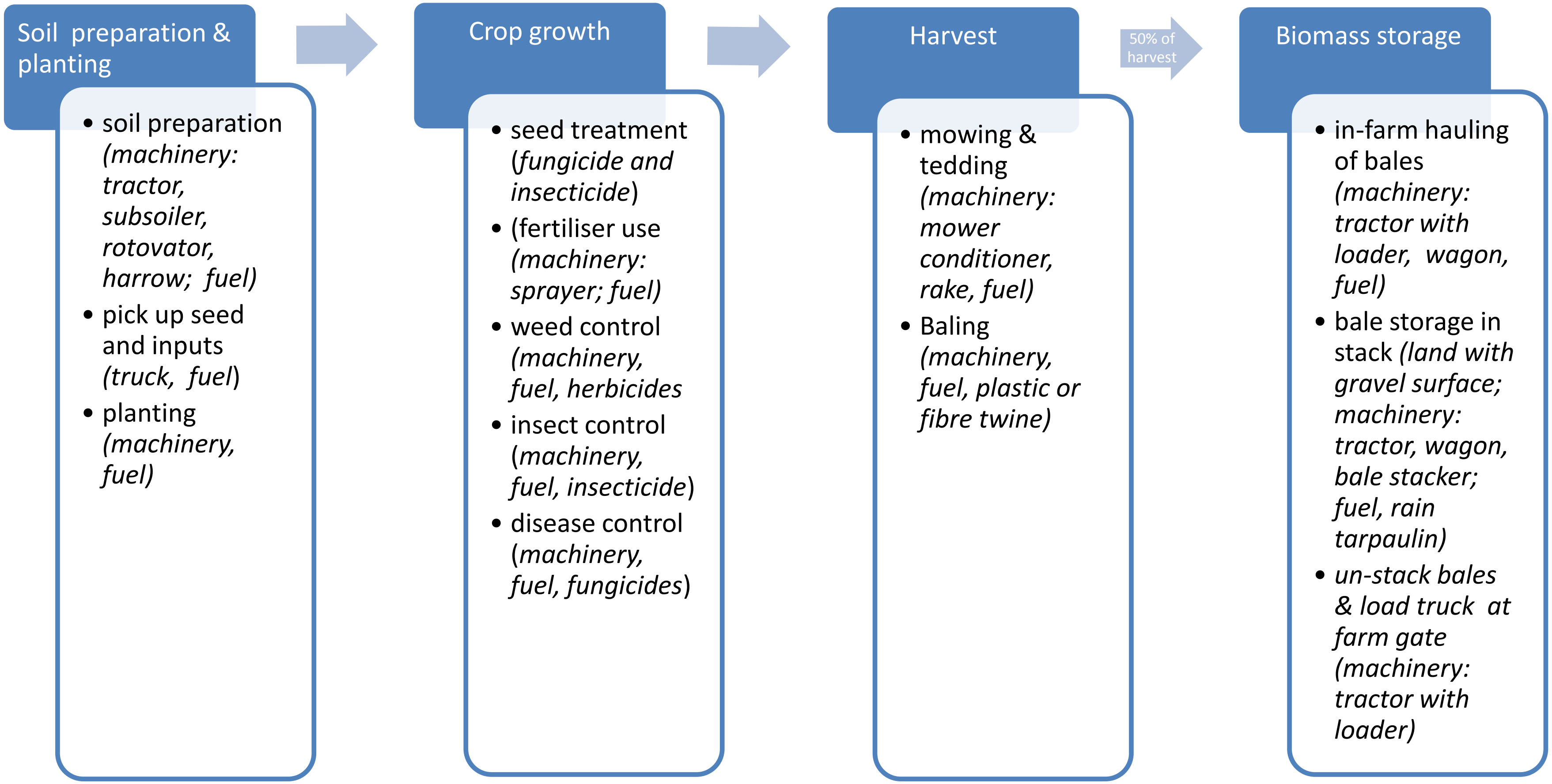
## Scope of the study

This is a ‘cradle to farm gate’ study. It covers environmental impacts from all triticale production steps: raw materials extraction for use in farming equipment and activities (the cradle), operations to grow the biomass, biomass harvesting, on-farm storage of the biomass harvested at certain times of year (to suit synchrony of feedstock supply to the gasification plant) and its transport within-farm from the field to the farm gate. The reference year for the present study is 2010. In order to quantify energy consumption, data from the above steps include the relevant primary energy, the energy embodied in machinery and agrichemical inputs to cropping and harvesting and transport to the storage stack and finally to the farm gate.

The geographic scope of the study, in terms of field inputs such as crop environmental responses and biomass yield, is quite broad due to the choice of triticale as biomass species. It has been proven to grow successfully in all arable cropping regions of New Zealand. This is because many triticale cultivars grow during autumn, winter and spring, so do not require summer rainfall. Nevertheless, field trials were located in the Southland region, since its summer climate includes higher mean rainfall than most arable cropping regions, making it suitable to test a double-cropping scenario with triticale grown from autumn to early midsummer, followed by a quick summer crop, such as sunflower. However, this LCA is for triticale as the sole crop per year, so is more widely applicable in NZ than just climates with summer rainfall such as Southland.

The system boundary from this study is detailed in Figure 1. While the system is quite inclusive, cut-off decisions were made to exclude the emissions from employees in the supply chain and also manufacturing & maintenance inputs for minor equipment such as tractor implements (the tractors themselves are included). Fluxes in soil carbon are also omitted, in line with the current IPCC practice. However, triticale is an annual species requiring yearly soil cultivation pre-planting, which causes loss of CO2 from the soil and there is no below-ground storage of carbon in persisting plant structures (such as rhizomes in giant miscanthus).

No allocation was required as the whole Triticale plant is put to a single use.



**Soil preparation & planting**

- soil preparation *(machinery: tractor, subsoiler, rotovator, harrow; fuel)*
- pick up seed and inputs *(truck, fuel*)
- planting *(machinery, fuel)*

**Crop growth**

- seed treatment (*fungicide and insecticide*)
- (fertiliser use *(machinery: sprayer; fuel)*
- weed control *(machinery, fuel, herbicides*
- insect control (*machinery, fuel, insecticide*)
- disease control (*machinery, fuel, fungicides*)

**Harvest**

- mowing & tedding *(machinery: mower conditioner, rake, fuel)*
- Baling *(machinery, fuel, plastic or fibre twine)*

50% of harvest

**Biomass storage**

- in-farm hauling of bales *(machinery: tractor with loader, wagon, fuel)*
- bale storage in stack *(land with gravel surface; machinery: tractor, wagon, bale stacker; fuel, rain tarpaulin)*
- *un-stack bales & load truck at farm gate (machinery: tractor with loader)*

**Figure 1 : Flow diagram – Farming operations for the annual type species triticale. The crop production stages are in the dark background boxes, the activities in the front boxes and inputs in parentheses and italics.**

## Life Cycle Inventory (LCI)

The aim of this LCA is to identify the most appropriate LCI input values to assess triticale production of biomass in New Zealand conditions. The methods used will require a more detailed description since we developed our own calculation spreadsheet rather than use dedicated LCA software.

The first subsection in this LCI section describes the inputs to the inventory that characterise the operations required to grow triticale biomass, from cradle to farm gate. The next subsection describes the structure of the Operations Calculation Sheet. The principle task of the LCI process is to populate that spreadsheet with appropriate values.

Data collection for the triticale field experiments began in 2010 and for the LCI it began during mid-2013. This procedure makes an inventory of inputs to and outputs from a triticale biomass production system. These LCI data were quantified and expressed relative to the functional unit: *cultivation of one hectare of triticale shoot biomass*, for reasons explained in the section 'Goal of the study'. The energy costs and footprints for GWP and EUT are also calculated for the other functional unit*: 1.0 tonne dry mass of triticale (contained within biomass of known moisture content, at the farm gate)*.

Literature review had already identified several papers on LCA of biofuels and biomass crops for use in bioenergy generation. While there were large enough differences between studies in the calculated values for energy balance and environmental impacts to be wary, there was an adequate general pattern of results to guide a well-informed decision on which impact factors should be prioritised in this study. It was necessary to focus on only a small number due to limited time and other resources.

### LCI inputs on biomass crop production operations (including NZ field trials)

This section describes the process of selecting the most appropriate values for a large number of inputs to the LCI that quantify the operations involved in growing and handling triticale biomass. This section will set the stage for the section where the methods for designating (choosing or calculating) LCI values for the impacts on energy use and the environment are provided.

Crop management factors in the spreadsheet were obtained from existing New Zealand information on triticale and related cereal grain species harvested for whole crop silage, as dairy cow feed. This commercial practice involves harvesting earlier than the optimum for a biomass crop for gasification, which is harvested shortly before grain harvest time. This practice aims for moisture content as low as can be feasibly achieved under field conditions. Many input factors related to crop management were contained within a 2005 production guide on whole crop cereal silage written by arable crops researchers (see Triticale Protocol document).

#### *LCI: selecting tractors and diesel fuel use rates*

Tractor fuel use was a major variable contributing to energy use and GWP and since recording tractor fuel use during field trials was not practicable it was necessary to rely on literature. The NZ reference on this topic is a farm budget manual from Lincoln University (Faculty of Commerce, 2012) that includes values on the rate of fuel use in tractors and farm equipment. The fuel data source for that manual was based on the University of Nebraska tractor test lab (University of Nebraska, 2014) the same source used by various European studies. That analysis identified the calculation constant for tractor fuel use to be 0.3L/hr per kW engine size doing heavy work, giving fuel consumption as 18 L/hr for a 60 kW tractor or 23 L/hr for a 77 kW tractor. These tractor sizes are being used in small to medium scale NZ triticale production.

This LCI takes the preferred NZ farming approach for a typical grain crop, which is to avoid mouldboard ploughing in favour of subsoiling, followed by horizontal rotary cultivation. The NZ manual, citing the Nebraska tractor test station report, lists the fuel use for subsoiling as 15 L/ha and for ploughing as 21 L/ha (tractor sizes converge in this calculation, since a larger tractor will cover a hectare more quickly). The LCI procedure first chose, as spreadsheet input values, the fuel use rate for each farming operation (see Appendix A). The selected rate for subsoiling, 18 L/ha, is the midpoint of the values in the manual for subsoiling and ploughing, to avoid under-stating fuel impacts. Fuel use for other operations (e.g., agrichemical spraying) ranged as low as 1.0 L/ha, when tractors pull wide but light implements at higher speed, covering a whole hectare much more quickly.

### *LCI: selecting fertiliser rate inputs*

Fertiliser inputs need to be accurate, since research has indicated that N fertiliser is a major contributor to GWP via $N_2O$ emissions (Schmidt et al, 2000) and its production also contributes a large share of the total energy consumed in crop production (Kaltschmitt et al, 1997). The other environmental impact category assessed in this study is eutrophication, EUT. This is primarily impacted by fertiliser use as well, in particular by both P and N. N use has several routes of impact, while P fertiliser has a direct route to waterway eutrophication; mainly if it is carried to surface waterways with eroded soil.

**Nitrogen (N).** The starting point in quantifying N fertiliser inputs is the amount of N removed in the crop. For forage cereals up to 280 kg N/ha is removed; the rule of thumb is that N removal is about 15 kgN/tDM harvested.

If a soil at the low end of the fertility range supplies 100 kgN/ha, then the balance required in fertiliser is up to 180 kgN/ha. Less than a third of this, e.g. 20–60 kgN/ha (equivalent to 40–120 kg/ha urea at 50% N) should be broadcast and incorporated prior to the last cultivation or applied soon after emergence. This is to minimise nitrate leaching before the plant root system is well developed to capture nitrate. Perennials have only one such year over the life of the planting, but leaching risk is high every year in an annual crop.

The LCI procedure used the following N fertiliser rates: 40 kg N/ha at planting and 110 kg N/ha following plant establishment. The triticale trials in Southland used similar rates.

**Phosphorus (P)**. Crop removal in the harvested crop may exceed 36 kgP/ha. Soil should be tested to see if this full rate of replacement is required (it does not if the soil test for P is more than 20 µg/ml). The LCI procedure used as input the rate 40 kg P/ha, which should be incorporated into the soil each year before planting.

**Potassium (K).** Crop removal is typically 200 kgK/ha in a biomass harvest, although most NZ soils have large K reserves. The only issue is that mineralised K may not be released quickly enough to supply plants during rapid growth. This is addressed with a typical application of 50 kg K/ha.

**Lime.** In South Island NZ soils where cereals are widely grown it is usually necessary to correct soil pH and add calcium (lime) periodically. The typical annual average rate required is 0.5 t/ha-yr.

### *LCI: selecting pesticide inputs*

An annual triticale crop requires a number of pesticide inputs, as identified in the publication on whole crop cereal silage. The agrichemicals used as LCI inputs were identified through information from the manufacturers, and confirmed by experienced arable crop researchers. The following products are used as the basis for calculating the inputs involved in their manufacture.

Fungicides. Several fungal diseases must be protected against, despite resistance to specific fungi having been bred into new cultivars. Protection during early seedling growth from several diseases can be achieved by seed treatment with a fungicide. The product selected is fluquinconazole. There is often disease pressure in the field requiring treatment with the product epoxyconazole, sometimes mixed with a second type of fungicide.

Insecticides. Some pests that attack young plants can be controlled by insecticides applied to the seed before planting. The recommended product is with imidacloprid. Later in the growing season other insects may build up but are controlled with lambda-cyhalothrin.

Herbicides. As an annual crop newly-emerging triticale plants are susceptible to weed competition. As a low-value arable crop it cannot be hand weeded on a large scale like some organic horticultural crops, so herbicides are needed. There is a wide range of soil active herbicides that can be used on triticale with reasonable success. The product used in the LCI is a mixture of three active ingredients (diflufenican + mesosulfuron + iodosulfuron) which control a wide range of both grasses and broadleaf weed species from a single application.

### *LCI: biomass yield inputs*

The NZ trials used for the BTSL project, as well as commercial experience with triticale, provide realistic biomass yield values to assess triticale energy yield per ha and the energy balance against inputs. Productivity of triticale was quantified in a series of field trials in the Southland region of NZ. These indicated a range of whole crop DM yields in areas with relatively deep fertile soil from 20 to 26 tDM/ha, higher than other cereal grain species.

An experiment in the Chatton area in 2010-11 was spring sown and two new triticale breeding lines yielded an average of 22.5 tDM/ha in that site with good arable soil. This is surprisingly close to the yields of autumn sown cultivars, which have a longer growing season and are expected to yield somewhat higher. Triticale yield data were also measured in two autumn-sown trials in 2012–13 in late April, one in prime arable land near Waiwera and the other in a more ‘marginal’ site near Balfour. At the more marginal site (a drier district with lighter soil and lower base fertility due to a history of being heavily cropped) the yield was 17.2 tDM/ha. At the Waiwera site the soil was heavier textured, less cropped with better base fertility and adequate moisture due to typical rainfall. The biomass mean yield was 26 tDM/ha.

Effect of harvest moisture content on biomass yield. The moisture content of biomass when harvested in mid-February in the Chatton trial was 39%. This indicates that the date of harvest was 3-4 weeks before plants would have dried to their lowest potential field moisture of about 15%, making the biomass directly usable for gasification; however waiting that long also risks the loss of the biomass if seed shatters during baling. The optimal compromise is likely to result from cutting before 15% moisture (to avoid reduced DM from loss of seed) but not when moisture is high enough that field drying in windrows prior to baling would take more dry days than are likely.

The two autumn-sown sites were harvested at quite different moisture contents. The rates of biomass moisture loss differed as a result of site differences in both soil fertility and rainfall. At the more marginal site (in a drier district with lighter soil and lower base fertility due to a history of being heavily cropped) the moisture content was already <15% and suitable for gasification. This was associated with a lower yield, 17.2 tDM/ha. At the Waiwera site the soil was heavier in texture, less cropped and with better base fertility and adequate moisture due to normal rainfall. At the time of DM yield assessment the moisture content was 34% and the biomass mean yield was 26 tDM/ha. Having such a high biomass yield tends to delay maturation. Ideal timing for biomass harvest would have been 1-2 weeks later; but the biomass would probably still require field drying in windrows before baling.

The DM yield used as input to the LCI, based on the above results, was 22 tDM/ha at harvest, reduced by 10% to allow for handling losses during harvest and storage, so 19.8 tDM/ha at the farm gate. These NZ yield data are used with a literature-reported measurement of the Lower Heating Value (LHV) of triticale biomass to calculate the gross and net energy yield (see section on Energy Balance).

### *LCI: harvest timing inputs*

The main criterion for timing harvest is moisture content, as was discussed in the previous subsection on yield influences. It would be ideal if another criterion could be to harvest triticale when the N content is quite low (as can be done with biomass crops that are mostly stems). Triticale, however, has a large part of its mass as grain and that has a high protein (and N) content. Therefore, N content is not a feasible timing criterion.

## Operations Calculation Sheet

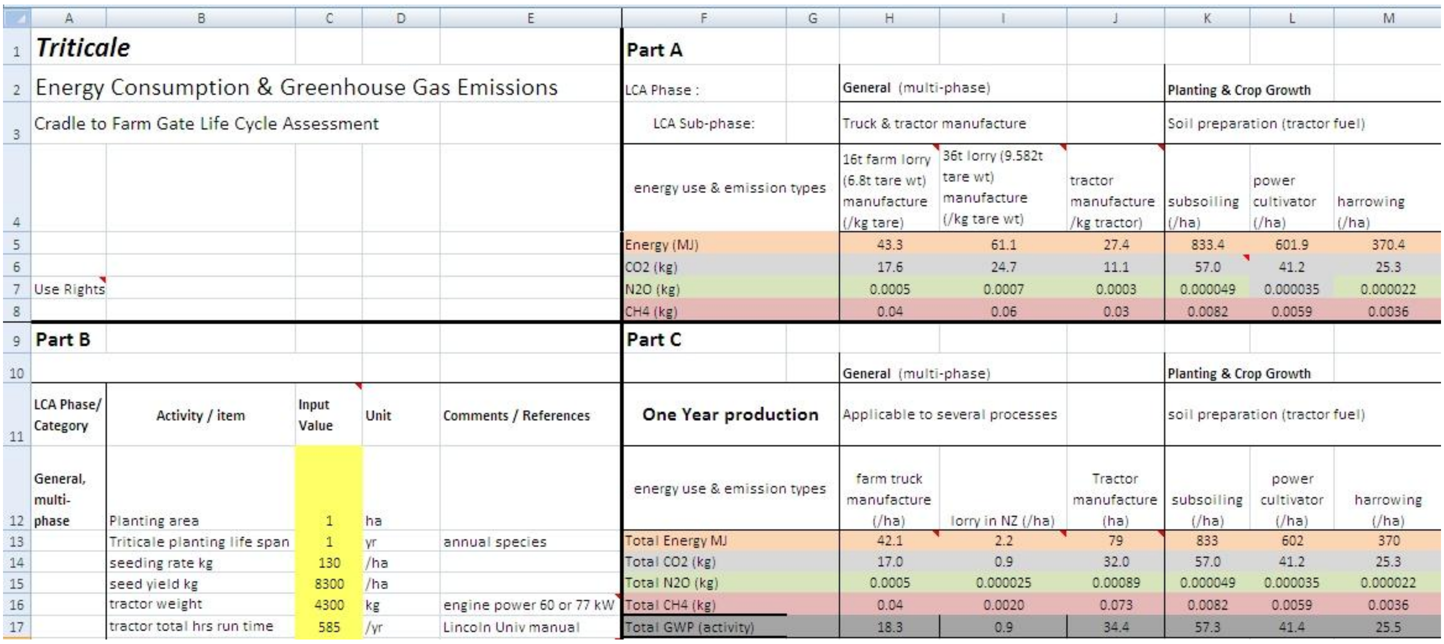
Populating the Excel™ calculation spreadsheet with values appropriate for NZ constituted the principle task of the LCI process. The three main calculations from the spreadsheet are Energy consumption (GJ/ha) and the two environmental impacts Global Warming Potential ($GWP_{100}$, as $CO_2e$/ha) and Eutrophication ($EUT_{100}$, as $PO_4e$/ha), both on a 100 year basis.

The Operations Calculation Sheet was organised in three parts. These are described in detail in Appendix A. Parts A and B are described here and reported in the following subsection of this METHODS section, while Part C (spreadsheet results) is populated with values presented in the RESULTS section.

Figure 2 is an image of the upper left corner of the Operations Calculation Sheet, with a few columns of Part A in the upper right (with Part C underneath) and a few rows of Part B on the left. Part A shows the rate of energy use or emissions of GHG across the top of the spreadsheet in 38 columns, grouped under three phases: 1) Planting & Crop Growth; 2) Harvest & Handling; and 3) Storage. Part C looks similar, but shows the total impact for each operation, usually on per ha basis.

Part B of the Operations Calculation Spreadsheet contains a long list of input values that are either engineering constants or selected values of variables assessed in part on how well they fit the real data from the 3-year NZ field trials. Some of these values are illustrated in Tables 1, 2 and 3.

Individual Part A input values that are only shown in summary form in tables in the RESULTS section are reported in the following METHODS text. The values derived in Part C of the spreadsheet are reported in the RESULTS section.



| | A | B | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | ***Triticale*** | | | | | **Part A** | | | | | | | |
| 2 | Energy Consumption & Greenhouse Gas Emissions | | | | | LCA Phase : | | **General** (multi-phase) | | | **Planting & Crop Growth** | | |
| 3 | Cradle to Farm Gate Life Cycle Assessment | | | | | LCA Sub-phase: | | Truck & tractor manufacture | | | Soil preparation (tractor fuel) | | |
| 4 | | | | | | energy use & emission types | | 16t farm lorry (6.8t tare wt) manufacture (/kg tare) | 36t lorry (9.582t tare wt) manufacture (/kg tare wt) | tractor manufacture /kg tractor) | subsoiling (/ha) | power cultivator (/ha) | harrowing (/ha) |
| 5 | | | | | | Energy (MJ) | | 43.3 | 61.1 | 27.4 | 833.4 | 601.9 | 370.4 |
| 6 | | | | | | CO2 (kg) | | 17.6 | 24.7 | 11.1 | 57.0 | 41.2 | 25.3 |
| 7 | Use Rights | | | | | N2O (kg) | | 0.0005 | 0.0007 | 0.0003 | 0.000049 | 0.000035 | 0.000022 |
| 8 | | | | | | CH4 (kg) | | 0.04 | 0.06 | 0.03 | 0.0082 | 0.0059 | 0.0036 |
| 9 | **Part B** | | | | | **Part C** | | | | | | | |
| 10 | | | | | | | | **General** (multi-phase) | | | **Planting & Crop Growth** | | |
| 11 | **LCA Phase/ Category** | **Activity / item** | **Input Value** | **Unit** | **Comments / References** | **One Year production** | | Applicable to several processes | | | soil preparation (tractor fuel) | | |
| 12 | **General, multi-phase** | Planting area | 1 | ha | | energy use & emission types | | farm truck manufacture (/ha) | lorry in NZ (/ha) | Tractor manufacture (ha) | subsoiling (/ha) | power cultivator (/ha) | harrowing (/ha) |
| 13 | | Triticale planting life span | 1 | yr | annual species | Total Energy MJ | | 42.1 | 2.2 | 79 | 833 | 602 | 370 |
| 14 | | seeding rate kg | 130 | /ha | | Total CO2 (kg) | | 17.0 | 0.9 | 32.0 | 57.0 | 41.2 | 25.3 |
| 15 | | seed yield kg | 8300 | /ha | | Total N2O (kg) | | 0.0005 | 0.000025 | 0.00089 | 0.000049 | 0.000035 | 0.000022 |
| 16 | | tractor weight | 4300 | kg | engine power 60 or 77 kW | Total CH4 (kg) | | 0.04 | 0.0020 | 0.073 | 0.0082 | 0.0059 | 0.0036 |
| 17 | | tractor total hrs run time | 585 | /yr | Lincoln Univ manual | Total GWP (activity) | | 18.3 | 0.9 | 34.4 | 57.3 | 41.4 | 25.5 |

**Figure 2. Partial screen view of Triticale Operations Calculation Sheet showing input values (A), constants and conversions (B) and outputs for the LCI (C).**

**Table 1: A portion of Part B in the Operations Calculation Sheet; values to apply to agricultural operations to grow triticale over 1 year. The four production phases are: 1) Planting & crop growth; 2) Harvesting & handling; 3) Storage.**

| LCA Phase | Activity/Product | Unit | Input Values |
|---|---|---|---|
| **Planting & Crop Growth** | Subsoiling | Runs (/ha) | 1 |
| | | Fuel use (L/ha) | 18 |
| | Cultivating | Runs (/ha) | 1 |
| | | Fuel use (L/ha) | 13 |
| | Harrowing | Runs (/ha) | 1 |
| | | Fuel use (L/ha) | 8 |
| | Sowing | Runs (/ha) | 1 |
| | | Fuel use (L/ha) | 4 |
| | Irrigation | (L/ha) | 0 |
| | Seed Trt with insect./fungic. | Fuel use (L/ha) | 0 |
| | | Runs (/ha) | 1 |
| | herbicide applications | Fuel use (L/ha) | 1 |
| | | Runs (/ha) | 1 |
| | Insecticide applications | Fuel use (L/ha) | 1 |
| | | Runs (/ha) | 1 |
| | Fungicide applications | Fuel use (L/ha) | 1 |
| | | Runs (/ha) | 1 |
| | Fertiliser Applications | Fuel use (L/ha) | 3 |
| | N | Runs (/ha) | 1 |
| | | rate (kg/ha) | 150 |
| | P | Runs (/ha) | 1 |
| | | rate (kg/ha) | 25 |
| | K (applied with N) | Runs (/ha) | 1 |
| | | rate (kg/ha) | 50 |
| | Lime | Runs (/ha) | 1 |
| | | rate (kg/ha) | 500 |
| **Harvesting & Handling** | Harvest Mowing/tedding | Runs (/ha) | 1 |
| | | Fuel use (L/ha) | 6 |
| | Baling | Runs (/ha) | 1 |
| | | Fuel use (L/ha) | 4 |
| | Haul + Stack or Load Bales | Runs (/ha) | 2 |
| | | Total Fuel use (L/ha) | 2 |
| **Storage** | Unstack + Load Bales | Runs (/ha) | 1 |
| | | Fuel use (L/ha) | 2 |

**Table 2: A portion of Part B in the Operations Calculation Sheet; physical constants of the crop triticale. HHV and LHV are also called Gross and Net Calorific Values.**

| Item | Constant | Unit |
|---|---|---|
| Yield (single year, 3 years per site) | 19.8 | tDM/ha/year |
| Carbon Content | Na | kgC/tDM |
| Hydrogen Content | Na | kgH/tDM |
| Higher Heating Value (HHV)* | 18.62 | GJ/tDM |
| Lower Heating Value (LHV)* | 17.10 | GJ/tDM |
| Crop Gross Energy Yield (LVH x DM) | 338.6 | GJ/ha-yr |

*also called GCV and NCV (gross & net calorific value)

**Table 3: A portion of Part B in the Operations Calculation Sheet; diesel fuel and farm machinery physical constants used to calculate energy use for 1 ha of triticale production over 1 year.**

| item | constant | Unit | source |
|---|---|---|---|
| Diesel consumer energy (NZ value from MED) | 38.4 | MJ/L | MED Energy Data File 2011 |
| Diesel conversion factor, consumer to primary energy | 1.207 | | Barber 2011b |
| Diesel primary energy use per litre | 46.3 | MJ/L | Barber 2011b |
| Diesel GWP (embodied + burning) | 3.18 | kg CO2e/L | McDevitt 2011 |
| truck/tractor life span | 12 | Yrs | |
| tractor weight | 4300 | Kg | |
| Truck 36t lorry weight | 9582 | Kg | |
| Farm truck 16t lorry weight | 6800 | Kg | |
| Tractor total use on farm | 585 | hours/yr | |
| Tractor use* | 4.7 | hours/yr | |
| Fuel use in farm truck* | 14 | L/100km | |
| distance (return): fertiliser store to farm | 30 | Km | |
| diesel fuel use by 36t truck (lime transport)* | 30 | L/100km | |
| distance (return): lime to Southland | 200 | Km | |

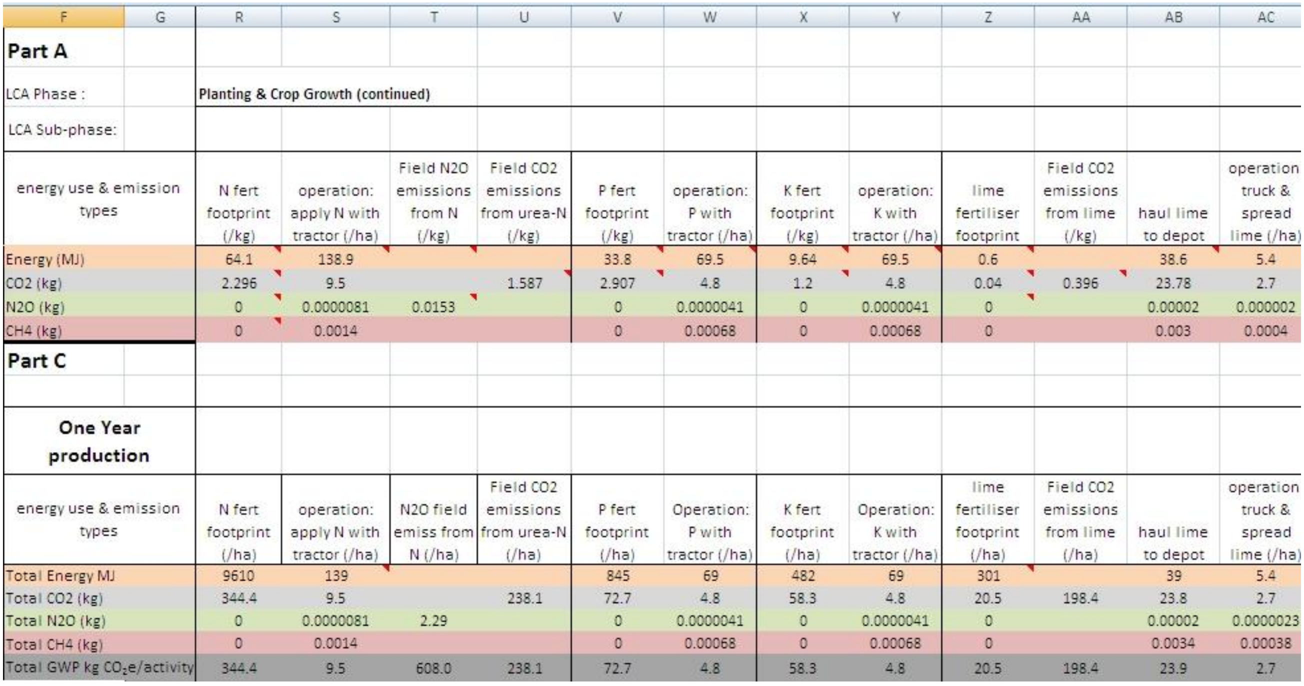
## LCI-designated impacts of triticale production on energy use and the environment

The following subsections describe the inputs to the Operational Calculation Spreadsheet that quantify energy use and impacts on GWP of each triticale production operation. This procedure generally makes use of LCA software that integrates LCI databases. When software to access such databases is not used (as in this LCA), the required values are compiled or calculated by assessing which values reported from research literature are most appropriate and by using direct knowledge of local (New Zealand) values.

### *LCI designated inputs on energy use*

The calculated rate of energy use for a single operation of each type is calculated in Part A of the Operational Calculation Spreadsheet, as in Figure 3.

**Figure 3. An image from Parts A and C of the Triticale Operations Calculation Sheet. Part C show the calculated values for the 20-year energy use (top row of the lower band) and GWP emissions (bottom shaded row) from each fertiliser operation.**



| F | G | R | S | T | U | V | W | X | Y | Z | AA | AB | AC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Part A** | | | | | | | | | | | | | |
| LCA Phase : | | **Planting & Crop Growth (continued)** | | | | | | | | | | | |
| LCA Sub-phase: | | | | | | | | | | | | | |
| energy use & emission types | | N fert footprint (/kg) | operation: apply N with tractor (/ha) | Field N2O emissions from N (/kg) | Field CO2 emissions from urea-N (/kg) | P fert footprint (/kg) | operation: P with tractor (/ha) | K fert footprint (/kg) | operation: K with tractor (/ha) | lime fertiliser footprint | Field CO2 emissions from lime (/kg) | haul lime to depot | operation truck & spread lime (/ha) |
| Energy (MJ) | | 64.1 | 138.9 | | | 33.8 | 69.5 | 9.64 | 69.5 | 0.6 | | 38.6 | 5.4 |
| CO2 (kg) | | 2.296 | 9.5 | | 1.587 | 2.907 | 4.8 | 1.2 | 4.8 | 0.04 | 0.396 | 23.78 | 2.7 |
| N2O (kg) | | 0 | 0.0000081 | 0.0153 | | 0 | 0.0000041 | 0 | 0.0000041 | 0 | | 0.00002 | 0.000002 |
| CH4 (kg) | | 0 | 0.0014 | | | 0 | 0.00068 | 0 | 0.00068 | 0 | | 0.003 | 0.0004 |
| **Part C** | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| **One Year production** | | | | | | | | | | | | | |
| energy use & emission types | | N fert footprint (/ha) | operation: apply N with tractor (/ha) | N2O field emiss from N (/ha) | Field CO2 emissions from urea-N (/ha) | P fert footprint (/ha) | Operation: P with tractor (/ha) | K fert footprint (/ha) | Operation: K with tractor (/ha) | lime fertiliser footprint (/ha) | Field CO2 emissions from lime (/ha) | haul lime to depot | operation truck & spread lime (/ha) |
| Total Energy MJ | | 9610 | 139 | | | 845 | 69 | 482 | 69 | 301 | | 39 | 5.4 |
| Total CO2 (kg) | | 344.4 | 9.5 | | 238.1 | 72.7 | 4.8 | 58.3 | 4.8 | 20.5 | 198.4 | 23.8 | 2.7 |
| Total N2O (kg) | | 0 | 0.0000081 | 2.29 | | 0 | 0.0000041 | 0 | 0.0000041 | 0 | | 0.00002 | 0.0000023 |
| Total CH4 (kg) | | 0 | 0.0014 | | | 0 | 0.00068 | 0 | 0.00068 | 0 | | 0.0034 | 0.00038 |
| Total GWP kg CO$_2$e/activity | | 344.4 | 9.5 | 608.0 | 238.1 | 72.7 | 4.8 | 58.3 | 4.8 | 20.5 | 198.4 | 23.9 | 2.7 |

Fertiliser impact on energy use. The calculated energy use per kg N in urea is 64.1 MJ/kg, while for calcium ammonium nitrate (CAN) it is 42.5 MJ/kg, both based on values reported in New Zealand studies (Ledgard et al, 2011; Zonderland-Thomassen et al, 2011). The urea value is used here since for arable and biomass crops the more expensive N fertiliser, CAN, is little used. The energy input to make 150 kg N fertiliser (for 1.0 ha of triticale) was very high, 9610 MJ/ha, plus 139 MJ/ha for field application. Among the other nutrients, phosphorus is the one with the next greatest, but much lower, impact from its production on energy use (845 MJ/ha) since it is bulky and shipped a long distance (usually from North Africa). Lime (calcium carbonate) is required every few years on many cereal-growing sites at an average annual rate of 0.5 t/ha. Lime is mined in NZ but is bulky to grind and ship. The processing value used in NZ (Barber 2011a) is 0.6 MJ/kg lime and the rate used for triticale cropping has an associated energy consumption of 330 MJ/ha (including fuel for 200 km transport to a local depot). Production of the nutrient potassium is in the same impact range at 482 MJ/ha.

Diesel tractor fuel impact on energy use. Calculating primary energy input from fuel use was straightforward, since a single NZ –based value was used (46.3 MJ/L of diesel, from Barber 2011a). See Appendix B for an explanation of how this value was chosen, since energy content of fuels does vary with source of petroleum and processing method used. Total primary energy also contains 'fugitive' energy use before the diesel fuel reaches the consumer. In this LCA the value for subsoiling was calculated from fuel use of 18 L/ha and the energy content value of 46.3 MJ/L, or 833 MJ/ha. The other farm operations ranged from 46 MJ/ha for spraying pesticides to 602 MJ/ha for power harrowing (Appendix A).

Pesticide impact on energy use. The LCI procedure for pesticides involved finding input values in MJ/kg active ingredient (ai) in the literature (Green, 1987; Audsley et al, 2009). The three fungicides and two insecticides considered as having good current control of pest in NZ have in common the feature of often having quite a large footprint per kg ai, but a very low use rate per ha. The designated input values, after converting to MJ/ha are:

| | |
|---|---|
| fungicides | epoxiconazole = 59 |
| | fluquinconazole = 16 |
| insecticides | lamdacyhalothrin = 0.2 |
| | imidacloprid = 10 |
| herbicides | diflufenican = 27 |
| | mesosulfuron-methyl = 5 |
| | iodosulfuron-methyl Na = 2 |

All but one fungicide have a smaller energy use footprint than from the 1 litre of diesel used for application (46.3 MJ/ha).

### *LCI designated inputs on Global Warming Potential (GWP)*

This study has focused on Global Warming Potential (GWP) as the primary environmental impact factor of interest to a project for replacing current fossil fuels, which are the main contributors to global GWP. The LCI was developed for the calculation of the GWP footprint from the production of triticale biomass (as feedstock for biofuel production). While energy use calculations for diesel fuel were able to use a single NZ value for primary energy, the calculation of GWP required formulas using values of emissions for each input product or operation. These are available in NZ for several fertilisers and diesel fuel, but most values for agrichemicals needed to be taken from overseas literature (e.g., Audsley et al, 2009; Bullard et al, 2001; Godard, 2013; Lal, 2004). The 2004 review by Lal revealed the wide range of GWP values reported for farm operations. When there was not a directly triticale-relevant value reported for an operation we opted for the representative value from the review by Lal (2004).

Fertiliser impact on GWP. This major impact category is often quantified in the literature on the basis of carbon dioxide equivalent impacts ($CO_2$e) per kg of fertiliser product. The preferred basis is per kg of fertiliser nutrient (elemental N, P or K).

The LCI designated values for production of fertiliser are:

- For N, the NZ study by Ledgard, et al, (2011) is the source of the GWP values for manufacture of the appropriate fertilisers and shipment to NZ. The calculated GWP for urea is reported as 1.056 kg $CO_2$e/kg urea (46% N), which converts to 2.296 kg $CO_2$e/kg N.
- For P, the parallel calculation (in triple superphosphate fertiliser) also used GWP values from Ledgard, et al, (2011). For P on a per kgP basis the reported value 0.596 $CO_2$e/kg of triple superphosphate (20.5% P) converts to 2.91 kg $CO_2$e/kg P.
- For K, (in potassium chloride) the GWP per kg KCl (50%K) value is 0.583 (Ledgard, et al, 2011), which converts to 1.17 kg $CO_2$e/kg K. The P and K elemental analyses used here are from commercial NZ fertiliser (Ravensdown).
- For Lime (calcium carbonate) the GWP value used was 0.396 kg $CO_2$e/kg lime (Barber, 2011), the IPCC value for loss of $CO_2$ from soil-applied lime to air.

In Part C of the calculation spreadsheet the above fertiliser impacts on GWP are all converted to per ha basis, using application rates described in section "LCI: selecting fertiliser rate inputs" of this report. The impact of N fertiliser on GWP is shown in the results. The GWP footprint for P fertiliser is 73 $CO_2$e/ha; for K it is 58 and for lime it is 21 $CO_2$e/ha. The total for N, P and K is shown in the RESULTS section.

A second and larger category of fertiliser impact on GWP is soil emissions of GHGs. These occur in response to application of fertilisers N and lime. The combined N impact, including direct $N_2O$ emissions following field application and indirect $N_2O$ emissions from leached $NO_3$, is 0.0153 kg $N_2O$ /kg N applied, and was calculated form Bessou et al (2009). The rate for $CO_2$ emissions per quantity of urea N applied 1.587 kg $CO_2$/kg Urea applied. For lime, the rate is 0.396 kg $CO_2$/kg lime applied. The emission impact results for the fertiliser amounts used are presented in the RESULTS section, on per ha basis.

Diesel fuel impact on GWP. The LCI designated value for diesel fuel impact on GWP was 3.17 kg $CO_2$e/L diesel combusted. The source selected was McDevitt & Seadon (2011) since it included the appropriate calculation of impacts from transport of diesel to NZ. However, it only presented the collective GWP or kg$CO_2$e/kg diesel and did not give values for the main individual GHGs, as was the plan in this LCI. Values for $N_2O$ and CH4 were available from an Ecoinvent report (Nemecek, 2007), so were used instead and subtracted from $CO_2$e to give values for $CO_2$. The many other GHGs emitted by diesel combustion were excluded in this LCA; according to McDevitt & Seadon (2011) these result in lower GWP impact than $CH_4$. Since fuel use is quantified by volume rather than weight, intermediate input values used in the spreadsheet formulas are expressed as kg $CO_2$e per L, assuming a conversion factor of 0.853 kg/L diesel, before being converted to per ha basis.

The initial calculation of the environmental impact on GWP from diesel fuel use was made for the operation of subsoiling, which was used as a benchmark. All other operations using diesel fuel had their GWP values calculated in proportion to how their listed fuel use compared to that for subsoiling.

Pesticide impact on GWP. The LCI procedure designated input values for three soil active herbicides, diflufenican, mesosulfuron-methyl and iodosulfuron-methyl sodium, all contained in a single herbicide product, Othello D. The two fungicides identified for management of triticale diseases were epoxyconazole and fluquinconazole. The two insecticides were lamdacyhalothrin and imidacloprid.

The footprint for GWP was not available in the literature, but an analysis of a very large number of agrichemicals (Audsley et al, 2009) was able to develop a 'rule of thumb' as to how GWP values relate to the production energy values, with a factor of 0.069 kg $CO_2$e/ MJ energy used for agrichemicals production.

With the exception of one product, epoxyconazole (59 MJ/ha and 4 kg $CO_2$e/ha), the other agrichemicals had extremely low impacts on GWP, with values ranging from 0.2 – 1.9 kg $CO_2$e/ha. These were all smaller GWP footprints than from burning the one litre of diesel used for their application.

Other GWP impact categories. The indirect energy use and embodied GWP were input in the first part of the spreadsheet as values per kg of truck or tractor, so these are only presented in the RESULTS section, after being converted to a per ha basis.

### *LCI designated inputs on EUT*

EUT was the second impact category chosen. Eutrophication assesses the excessive presence of nutrients in water bodies causing uncontrolled growth of vegetation (e.g. algal bloom) that would not have occurred otherwise. The use of nitrogen and phosphorus-based crop fertilisers therefore has a high potential to cause eutrophication, due mainly to leaching of N and P-rich soil erosion. The data for calculating EUT are less available than for GWP, but more readily available than data on many of the health and toxicity impact factors that are not included in this LCA. For the impact category Eutrophication, due to the scarcity of data and budget/time constraints, it was decided to limit the analysis to the emissions from the diesel fuel burnt in trucks and tractors during cropping as well as the related emissions from fertiliser manufacture and application. While not comprehensive, it can be assumed that most emissions affecting eutrophication emanate from these two processes.

EUT is most often expressed in kg $PO_4$ equivalent, although it is sometimes expressed in kg N equivalent. Emissions of phosphorus and nitrogen and their derivates to the environment constitute the bulk of the EUT sources. In this study, the CML2001 (updated 04/2013) characterisation factors are used (CML, 2013). These factors are generally used in the LCA literature, and are assumed to be representative of NZ conditions.

### *EUT from N emissions*

The following factors (Table 4) are for the contributing N compounds involved in crop production.

**Table 4. Four emission types (forms of N) and the ir sources in the triticale production system. Many environmental features contribute to the values that have been determined as characterisation factors.**

| **Emission type** | **Source of emissions** | **CML Characterisation Factors (1kg = x kg $PO_4$)** |
|---|---|---|
| $N_2O$ | Both fuel & fert. use | 0.27 |
| Nox | Fuel use | 0.13 |
| $NH_3$ Ammonia | Fertiliser use | 0.35 |
| $NO_3$ Nitrate (surplus) | Fertiliser use | 0.1 |

These factors are used to convert the emissions of each type from the fertiliser operations in EUT indicator units (kg $PO_4$). The experiments and calculations of emissions from fertilisers in the literature, as cited in Hamelin et al (2012) have yielded a range of values. For triticale the middle of each range was chosen for each factor (Table 5).

**Table 5. Referenced emission ratios to quantify N emissions of each type. Values for NOx and NH3 are from Bessou (2012) who cited Ecoinvent database.**

| N Emission type/source | Direct ratios | Indirect ratios |
|---|---|---|
| $N_2O$ kg/kg diesel | 0.000003 | Unknown |
| $N_2O$ as % of N fert. | 1.5% | 1.5% of N surplus (leached $NO_3$) |
| $NO_x$ as % of N inputs | 0.6% | +1% of volatized $NO_x$ |
| $NH_3$ as % of N inputs | 2.6% | +1% of volatized $NH_3$ |
| $NO_3^-$ as % of N surplus | 1.0% | Unknown |

### *EUT from P emissions*

Erosion and surface runoff are the main sources of phosphorus release into water bodies. However, surface runoff of P can be assumed to be negligible if P fertiliser is incorporated into the soil (unless manure slurry is used). Leaching of P is lower than nutrient N due to its low solubility and strong adherence to soil surfaces.

The factor presented in Table 6 is for the contributing forms of P involved in crop production, expressed as $PO_4$.

**Table 6. The CLM Characterisation Factor applied to surplus P (after plant uptake) from applied fertiliser.**

| Emission to water | Source of emissions | CML Characterisation Factor (1kg = x kg PO4) |
|---|---|---|
| P (surplus) | Fertiliser | 3.06 |

Soil erosion, however, allows the attached P to be carried to waterways. Erosion rates in the Pacific region of the USA, where the climate is most similar to NZ were about 4 t/ha per year, typical for all crop/use types (Natural Resources Conservation Service, 2014). A much lower value was reported from a study of a complete small watershed in Norway (Farkas et al, 2013), where modelled sediment loss in agricultural (arable) soils was only 449 kg/ha with no autumn tillage and 1776 kg/ha with autumn tillage.

For this triticale LCA we followed the approach of Hamelin et al (2012) in Denmark. As part of an extensive LCA study they summarised several methods recently used to quantify P loss from nutrients applied to the soil and concluded that most results were in line with the simple calculation of losses for annual crop species as 5% of the net surplus of applied P fertiliser (mineral or manure slurry). In the triticale EUT calculation sheet the assumed fertiliser P rate was 25 kg/ha. Hamelin et al (2012b) presented calculated P losses of 22 kgP/ha applied to winter wheat, which took up 19 kgP/ha. The cereal crop was followed by a catch crop that took up all of the 3 kgP/ha of net surplus following the grain harvest. If there had been any P left as surplus, Hamelin et al (2012b) suggest that the P losses would be 5% of that.

Applying the same approach to a NZ triticale crop fertilised with 25 kgP/ha and with 19 kgP/ha uptake, the net surplus would be 6 kg/ha. A winter legume would probably take up all of this, but since this LCA is for triticale without a catch crop the P losses will be 5% of 6 kg. The CML Characterisation Factor of 3.06 is then applied to show the EUT impact.

## Life Cycle Impact Assessment methodology

*LCIA occurs as an overview of what has been covered in the LCI sections above, but is repeated here for completeness.*

In addition to the energy balance, the Life Cycle Impact Assessment (LCIA) and chemical flows were developed for two impact categories, both to a 100 year time horizon. These are Global Warming Potential (GWP) and Eutrophication (EUT). For GWP, the characterisation factors used in the LCIA for $CO_2$, $N_2O$ and $CH_4$ are from the most recent (AR5) IPCC report (IPCC, 2013). The RESULTS section will not specifically include an LCIA section but will integrate main components. Background considerations are presented here in METHODS.

### Net energy yield (Energy balance)

Determining the net energy balance effects of growing triticale biomass was the key motivation for performing a LCA, since the aim is to use the biomass as feedstock for bioenergy production, mostly as biofuel. The net energy yield at the farm gate is calculated as the gross energy yield (sometimes called the gross energy output) minus energy consumption or usage for the process (Bullard, et al, 2001). Gross energy in the case of triticale is energy stored in the crop biomass. Use of the Operations Calculation Sheet will largely be for calculating energy consumption, although it also contains values related to gross energy. The principal analysis will be on the cropping impacts on an area (ha) basis, as used in the first FU. However, for the purpose of the energy yield calculation, these will be converted to per tonne DM basis, enabling a direct comparison of these inputs costs to the gross energy yield. Net energy yield is then calculated by subtraction of energy consumption from gross energy. It should not be necessary to apportion these measures to individual cropping operations.

#### *Gross energy yield*

In addition to the calculation of energy consumption, gross energy output needs to be calculated using two factors. One is the measured NZ yield of triticale dry biomass (reduced by 10% to allow for handling losses in mass between standing in the field and loading at the farm gate). The dry mass yield value used for this is presented in the RESULTS section. The second factor is the energy content of the biomass, expressed as the Lower Heating Value (also called Net Calorific Value, a somewhat confusing term since it relates to gross rather than net energy yield). This is expressed on per tonne basis rather than per ha basis.

Overseas reported values of LHV for triticale vary somewhat since they were reported at different moisture contents. The value used as a proxy in this study is the LHV for wheat, 17.1 GJ/tDM, from Fehrenbach (2007). This can be directly related to the *second functional unit* of this study: 1.0 tonne dry mass of triticale (contained within biomass of known moisture content, at the farm gate).

#### *Energy consumption*

The inputs to calculate energy consumption (largely from diesel fuel, fertilisers and pesticides) are all available from literature and were used as inputs in the first part of the Operations Calculation Sheet (Appendix A) for each of the several operations to grow and store triticale biomass. Energy content for diesel fuel and fertilisers imported for use in NZ have been published (see LCI section on page 10). The quantity of diesel fuel used can be calculated with confidence within a reasonable range.

## Global warming potential (GWP)

The first of the two environmental impact factors assessed is GWP. It relates to radiative forcing of the gases selected in this LCA to be included in the GWP calculation, expressed as carbon dioxide equivalent ($CO_2e$). Radiative forcing is “a concept used to make quantitative comparisons of the strength of different human and natural agents in causing climate change. The radiative forcing of a chemical is calculated by quantifying the retained heat due to the presence of a particular gas” (McDevitt & Seadon, 2011).

GWP, also called the carbon footprint, was chosen as a central environmental impact factor because it is the most reported environmental indicator and there are more readily available data that detail elementary flows for this key impact category. The size of GWP is also of considerable interest to the agricultural export sector as consumers are increasingly ‘environmentally concerned’ and the GWP impact is a widely used environmental indicator reported for food products.

For GWP impacts of crop biomass production for bioenergy, the most relevant greenhouse gases (from use of diesel fuel and fertiliser) are $CO_2$ (the one used as the standard for comparison), nitrous oxide ($N_2O$), and methane ($CH_4$). The appropriate timeframe to assess radiative forcing effects is 100 years (GWP100), rather than 20 or 500 years, as it is the most commonly applied time horizon for GWP in LCA studies. However, the 100 years time horizon assumes that no impacts occur beyond 100 years following a pulse emission, which is not exact but constitutes a standard measure to compare emissions and production systems. Furthermore, GWP100 is one of the rare impact categories that does not depend on the site specific conditions of GHG emission, since it is assumed that the gases are “well mixed” in the atmosphere. The AR5 Assessment Report (IPCC, 2013) has adjusted the characterisation factors for radiative forcing to 265 for $N_2O$ and 30 for $CH_4$ to calculate the GWP100. Since new research indicates that $CH_4$ remains longer in the atmosphere than had been thought, and $N_2O$ alters faster, the new factors represent a decrease for $N_2O$ and an increase for $CH_4$ compared to the previous AR4 IPCC report (IPCC, 2006).

## Eutrophication (EUT)

EUT was the second impact category chosen. Eutrophication assesses the excessive presence of nutrients in water bodies causing uncontrolled growth of vegetation (including algae) that would not have occurred otherwise. The use of crop fertilisers therefore has a high potential to cause eutrophication, due mainly to leaching and soil erosion. The data for calculating EUT are less available than for GWP, but more readily available than data on many of the health and toxicity impact factors. For budget/time constraints, it was decided to focus on fuel consumption and fertiliser use as the only sources of eutrophication. While not fully comprehensive, we assumed that most emissions affecting eutrophication emanate from these two processes.

EUT is most often expressed in kg $PO_4$ equivalent, although it is sometimes expressed in kg N equivalent. Emissions of phosphorus and nitrogen and their derivates to the environment constitute the bulk of the EUT sources. In this study, the CML2001 (updated 04/2013) characterisation factors are used (CML, 2013), and are expressed in kg $PO_4$ equivalent. Like GWP, the widely-used timeframe for EUT in LCA studies is 100 years, so all uses of the abbreviation EUT in this LCA can be read as EUT 100.

# RESULTS

This section of the LCA Cradle to Farm Gate report includes the content usually called the Life Cycle Impact Assessment (LCIA). The Life Cycle Interpretation is included in the DISCUSSION section.

The outputs calculated in the spreadsheet for energy consumption and GWP impacts of triticale cropping are summarised in Tables 7 to 10. Table 11 summarises EUT impacts on per ha basis. The units are expressed for energy use in Gigajoules (1 GJ = 1000 MJ), GWP in kg $CO_2$ equivalent emissions (kg $CO_2$e/ha-yr) and EUT emissions to water in phosphate equivalents (kg $PO_4$e/ha-yr). Each of the table values is the total impact for a key operation or a group of related operations. The tables include all phases of JA cropping.

The overall pattern of energy consumption and GWP in Table 7 shows the percentage of the total emissions caused by each farming operation, and is referred to as a Contribution Analysis.

**Table 7. Contribution analysis of triticale farming operations (% of energy consumption and GWP for each operation).**

| Operations Contribution Analysis | | Percent of total energy use | Percent of total GWP 100 |
|---|---|---|---|
| **Phase** | **Operation** | | |
| **Planting and Crop Growth (P & CG)** | Soil preparation | 11.9% | 6.5% |
| | Planting + seed inputs | 4.6% | 3.2% |
| | Fertiliser N P K and lime (production + transport) | 74.5% | 27.4% |
| | Fertiliser (application + urea field emissions) | 1.8% | 55.8% |
| | Agrichemical production + transport | 0.8% | 0.4% |
| | Agrichemical application | 0.9% | 0.5% |
| | **Subtotal P & CG** | **94.6%** | **94.0%** |
| **Harvest & Handling (H & H)** | Harvest: Mowing/tedding | 1.2% | 0.7% |
| | Harvest: Baling | 1.2% | 0.7% |
| | Harvest: Haul bales | 0.6% | 0.3% |
| | Stack or load all bales | 0.6% | 0.3% |
| | **Subtotal H & H** | **3.7%** | **2.0%** |
| **Storage** | Un-stack & load bales; tarpaulin inputs | 0.9% | 1.2% |
| **Machinery Manufacture** | Farm truck (16t) manufacture | 0.3% | 1.0% |
| | Tractor manufacture | 0.5% | 1.8% |
| | | **100.0%** | **100.0%** |

The 75% contribution of fertiliser production is a very similar result to a triticale analysis by Godard et al in France (2013) where fertilisers contributed 71%.

The main difference between energy consumption and GWP patterns is that three quarters of energy use (but only a quarter of GWP) is from fertiliser manufacture, while over half of

GWP (but almost no energy use) is from soil emissions of GHGs. The two types of fertiliser impacts make up about 80% of GWP (see page 29 for more details on GWP).

## Net Energy Yield (Energy Balance) Results

### Energy consumption (inputs, GJ/ha)

Values in Table 8 are the total triticale energy use per ha for each of the several operations. The Grand Total of column 3 is the annual energy consumption, 15.2 GJ (15,172 MJ) per ha of triticale crop.

**Table 8. Energy consumption, GWP and EUT emissions on an area/time basis (/ha-yr). The crop production phases each contain several operations. Eutrophication was calculated by overall diesel fuel use and fertiliser use impacts, not by each operation.**

| Impacts: Energy, GWP & EUT | | Energy Use (GJ/ha) | GWP 100 (kg CO2e/ha) | EUT 100 (kg PO4e/ha) |
|---|---|---|---|---|
| **Phase** | **Operation** | | | |
| **Planting and Crop Growth (P & CG)** | Soil preparation | 1.81 | 124 | |
| | Planting + seed inputs | 0.70 | 61 | |
| | Fertiliser N P K lime (production + transport) | 11.31 | 522 | |
| | Field emissions (+ fertiliser application) | 0.28 | 1064 | |
| | Agrichemical production (+ transport) | 0.12 | 8 | |
| | Agrichemical application | 0.14 | 10 | |
| | **Subtotal P & CG** | **14.36** | **1791** | |
| **Harvest & Handling (H & H)** | Harvest: Mowing/tedding | 0.19 | 13 | |
| | Harvest: Baling | 0.19 | 13 | |
| | Harvest: Haul bales | 0.09 | 6 | |
| | Stack or load all bales | 0.09 | 6 | |
| | **Subtotal H & H** | **0.56** | **38** | |
| **Storage** | Un-stack & load bales; tarpaulin impacts | 0.13 | 23 | |
| **Machinery Manufacture** | Farm truck (16t) manufacture | 0.04 | 18 | |
| | Tractor manufacture | 0.08 | 34 | |
| **GRAND TOTAL** | **All phases** | **15.17** | **1905** | **3.87** |

Fertiliser production and soil preparation were the largest categories of energy use in Table 8. The collective impact of diesel fuel use is not apparent in Tables 7 and 8, but is presented in Table 9, where energy use is second only to fertiliser production. All other energy input categories were quite minor. Results for the two major input categories are presented in their own subsections below.

**Table 9. The largest contributors to Energy consumption and GWP emissions, expressed on an area/time basis (/ha-yr). Annualised values enable comparison to other biomass species on an area (per ha) basis.**

| Impact Contributors<br>Major Categories | Energy Use (GJ/ha) | GWP 100 (kg CO2e/ha) | EUT 100 (kg PO4e/ha) |
|---|---|---|---|
| Diesel fuel used in tractors | 3.06 | 210 | |
| Diesel fuel used in trucks | 0.10 | 11 | |
| Soil preparation | 1.81 | 124 | |
| Seed production | 0.46 | 42 | |
| N Fertilisers production | 9.61 | 344 | 2.96 |
| N Fertiliser soil emissions | n/a | 846 | |

### *Fertiliser use*

The combined total energy input for manufacture of N, P, K and lime is 11.3 GJ/ha. Most of this energy (9.6 GJ/ha) is consumed to produce N fertiliser. Details for the other nutrients were presented as part of the LC Inventory description in the Methods section. Compared to the perennial biomass species Mxg (with annualised fertiliser input = 1.16 GJ/ha) the fertiliser use and associated energy input for triticale (like that of many annual species) is nearly 10 times higher per ha, due in large part to the high annual requirement for N, but also because triticale requires more regular use of lime.

### *Diesel fuel use*

Fuel use represents direct energy (primary and ‘fugitive’) and totalled 3.06 GJ/ha (Table 9). Indirect energy use for production of trucks and farm machinery is much less and is shown in separate rows of Table 8.

### *Other operations*

Compared with fertiliser use and diesel fuel use all other operations in the production of triticale biomass have very low energy consumption. Even though the use of agrichemicals is extensive compared to perennial species such as giant miscanthus, the total energy cost of pesticide production was only 0.164 GJ/ha. Since triticale is propagated by seed, the seed itself is produced with a lower input than perennial species such as giant miscanthus and Jerusalem artichoke, which have vegetative propagules that are dug from the ground and are bulky to ship. Growing the seed does require many of the inputs used to grow a crop of triticale grain, however the seeding rate per ha represents only 2% of an 8 t/ha grain crop. When seed transport and planting fuel are added, the planting operation uses 0.7 GJ/ha (4.6%) of the 15.2 GJ/ha total energy inputs.

Once total energy consumption of all operations is known, the next part of an energy balance determination is to calculate gross and net energy yield.

### Gross energy yield (GJ/ha)

The average biomass yield of a triticale crop in this LCA (standing in the field at the time of winter harvest) is 22 tDM/ha. This is reduced by 10% to calculate the value of the yield loaded at the farm gate (to allow for handling and storage losses), leaving 19.8 tDM/ha per year of available biomass.

Gross energy yield is calculated as DM (t/ha) times the energy content. The value used for energy content of 1.0 tDM is the Lower Heating Value (Net Calorific Value). These are expressed on per tonne basis rather than per ha basis. The value used in this LCA is 17.1 GJ/tDM (see Table 2).

Triticale gross energy yield = 19.8 tDM/ha multiplied by 17.1 GJ/tDM = 338.6 GJ/ha.

### Net energy yield (to farm gate)

The energy balance at the farm gate is calculated as the gross energy yield minus energy consumption or usage for the process (Bullard et al, 2001). Gross energy in the case of crops such as triticale is solar energy transformed by photosynthesis into dry matter and stored in the biomass.

Net energy yield = gross energy yield (338.6 GJ/ha) minus energy consumption (15.2 GJ/ha) = 323.4 GJ/ha-yr.

The energy ratio (at the farm gate) between gross output and gross input was good (338.6/15.2 = 22). This is sufficiently positive that it will probably be feasible to produce biofuel from the biomass and still have a sufficiently positive overall energy balance.

For a direct link between energy analysis of the feedstock for gasification, the *functional unit* (FU) of the overall Cradle to Grave LCA = *1.0 tonne dry mass of triticale (contained within biomass of known moisture content, at the farm gate)*. Therefore, the net energy yield should be expressed on a /tDM basis, as energy use is in row 2 of Table 10:

- The energy to produce one tDM of triticale equals the energy consumption (15.2 GJ/ha-yr) divided by the DM yield (19.8 tDM/ha-yr), or 0.77 GJ/tDM;
- The gross energy contained in 1.0 tDM of triticale equals the gross energy yield (338.6 GJ/ha-yr) divided by the DM yield (19.8 tDM/ha-yr), or 17.1 GJ/tDM (which is actually the reference value, the triticale Lower Heating Value, used to calculate gross energy yield); and
- The net energy contained in one tDM of triticale equals the net energy yield (323.4 GJ/ha) divided by the DM yield (19.8 tDM/ha-yr), or **16.3 GJ/tDM** (also calculated by subtracting energy consumption (0.77 GJ/tDM) from the LHV (17.1 GJ/tDM).

**Table 10. Triticale energy use and GWP per ha or per tonne of dry mass (based on biomass yield of 19.8 tDM/ha).**

| **Energy use, GWP100 and EUT** (per ha and per year) | Energy use (GJ) | GWP100 (kg $CO_2$e) | EUT100 (kg $PO_4$e) |
|---|---|---|---|
| **Energy use or Emissions TOTAL (per ha)** | 15.17 | 1905 | 3.87 |
| **Energy use or Emissions TOTAL (per tDM)** | 0.77 | 96.4 | 0.2 |

Overall totals per ha for the three impact factors (energy use, GWP and EUT) are in Tables 8 and 10 and totals per tonne DM are in Table 10.

## Global Warming Potential (GWP) Results

GWP is the principal environmental impact category assessed in this LCA. Eutrophication results are discussed in the next section.

### GWP footprint of triticale production

The overall GWP of triticale production is 1905 kg $CO_2$e/ha. While most annual food or biomass crops would have similar or higher GWP, the perennial biomass species, giant miscanthus, has an overall annualised GWP of only 264 kg CO2e/ha. The calculations for GWP impacts per ha of triticale were done in the third part of the Operations Calculation Spreadsheet (Appendix A) for each of the several operations to grow and store triticale biomass. The totals for each operation are presented in Table 8. Results in the GWP column of Tables 7-10 are from the sum of the emissions from the three GHGs included in this LCA: $CO_2$, $N_2O$ and $CH_4$.

GWP impacts from triticale biomass production are similar in one respect to those for energy inputs, in that fertiliser use has the greatest impact. However, the largest impact of fertilisers on GWP was not from their manufacture, but from soil emissions of $N_2O$ and $CO_2$ (which makes no impact on energy consumption). Either soil emissions or fertiliser manufacture alone has more than double the GWP footprint of diesel fuel, which ranks third.

#### *Fertiliser use*

The largest GWP impact (1044 kg $CO_2$e/ha, double that of the production of all fertilisers) is from soil emissions of $N_2O$ and $CO_2$. The value in Table 8 includes 20 kg $CO_2$e for tractor fuel used in fertiliser application. Part of the GWP is from emissions of 198 kg $CO_2$ per ha following the use of fertiliser lime (using the IPCC calculated loss rate), but 846 kg $CO_2$e/ha is an indirect impact of N fertiliser (Table 9). The N emissions include both $CO_2$ and $N_2O$ and involve soil microbes. The small amount of $N_2O$ produced per ha (2.29 kg) has a large impact (608 kg $CO_2$e/ha) due to its potency as a GHG (265 times that of $CO_2$). The $CO_2$ soil emissions (238 kg $CO_2$e/ha) are from using 150 kgN/ha in a particular form of N fertiliser, urea; this is the most common form used in arable crops.

The total GWP impact for manufacture of N, P, K and lime is 522 kg $CO_2$e/ha (Table 8). Most of this impact is attributable to N fertiliser. Details for the other nutrients were presented as part of the LC Inventory description in the Methods section. To summarise, the N fertiliser footprint was 344 kg $CO_2$e/ha, the P footprint was 73, the footprint for K was 58 and the lime footprint from 500 kg/ha was 21 kg $CO_2$e/ha respectively.

#### *Diesel fuel use*

The GWP emissions related to tractor diesel fuel use totalled 210 kg CO2e/ha of triticale (Table 9). This was the third largest GWP impact, but only 19% of the total fertiliser impact.

#### *Other operations*

Compared with fertiliser use and diesel fuel use all other operations in the production of triticale biomass have very small impacts on GWP. Even though the use of agrichemicals is intensive compared to perennial species such as giant miscanthus, the total impact of pesticide production was only 8 kg $CO_2$e/ha. Growing the seed does require many of the inputs used to grow a crop of triticale grain, however the seeding rate is only 2% of an 8 t/ha dryland grain crop. When the GWP impact of seed transport and planting fuel are added to seed production, the planting operation uses 61 kg $CO_2$e/ha (3.2%) of the 1905kg $CO_2$e/ha total GWP (Table 7).

## Eutrophication (EUT) Results

The five sources of EUT from nitrogen compounds (four from N fertiliser and one from diesel emissions) had a total EUT impact of 2.96 kg $PO_4$e/ha (Table 11). This figure includes 2.07 kg $PO_4$e/ha-yr from the 5.91 kg of ammonia, released from soils after the application of urea fertiliser containing 150 kgN. Ammonia has a characterisation factor (CML, 2013) of 0.35 to convert kg ammonia to kg $PO_4$e.

**Table 11. Eutrophication resulting from triticale cropping. The gases emitted following nitrogen fertiliser use are N2O (which also is emitted from diesel fuel combustion), NOx, NO3 and NH3 . Emissions were lower from P than N fertiliser. The Characterisation Factors are from CML (2013), as in Table 4.**

| Emissions Source | Eutrophication (kg $PO_4$e/ha) |
|---|---|
| Diesel fuel use ($N_2O$) | 0.00022 |
| N fertiliser field emissions | 2.96 |
| P fertiliser field emissions | 0.92 |
| **Total kg $PO_4$e/ha** | **3.87** |

Phosphorus supply from the regional soils usually requires fertiliser supplementation to replace the P uptake by the crop. Soil testing is used to gauge the application rate needed. This LCI uses a rate of 25 kgP/ha, applied pre-planting. The surplus P after plant uptake is calculated to be 6 kgP/ha and 5% of that or 0.3 kg P/ha is the P loss to waterways estimated by the integrated method of Hamelin et al (2012). With a CML characterisation factor of 3.06 the EUT impact of P is 0.92 kg $PO_4$e/ha, considerably less than the contribution from ammonia and $N_2O$ derived from N fertiliser.

The total EUT impact from N and P fertilisers is 3.87 kg PO4e/ha-yr. In contrast, the EUT footprint for giant miscanthus is 0.46 kg $PO_4$e/ha-yr; a comparison is made in the discussion section.

## Impacts per tonne DM

The last aspect of the presentation of results is about the choice of units to quantify impacts of triticale production. Analyses in the previous sections all quantified energy consumption, GWP and EUT impacts of triticale biomass production on an area basis, which allows comparisons of environmental costs associated with the use of one hectare. When impacts are quantified per dry tonne of feedstock, as shown in Table 10, results can be used directly in an analysis of producing biofuel from biomass. This is one reason a second functional unit was described in this LCA. The second FU is also useful in relation to net energy yield, as illustrated above in the RESULTS subsection Net energy yield.

The triticale footprint sizes per tonne dry mass produced are: 0.77 GJ for energy consumption, 92 kg $CO_2$e for GWP and 0.2 kg $PO_4$e for EUT. Compared to the other two biomass species assessed, these impacts are higher than for JA and much higher than for Mxg. In terms of comparisons within NZ, production of the biomass crop triticale has slightly lower energy consumption and environmental impacts (GWP and EUT) than most current food and feed crops.

# DISCUSSION

Life cycle interpretation is an important component in an LCA. It involves discussion of the overall data set and whether the methodologies chosen influenced the results. It also discusses findings in terms of the 'hotspots' for each impact factor studied, in this case energy consumption, GWP and EUT impacts of biomass production and on-farm storage.

## Functional units

The underlying aim in doing Life Cycle Assessment of a product or process is (once the impacts have been examined) to make it feasible to minimise those impacts in the future.

The primary Cradle to Farm Gate functional unit is FU = *cultivation of one hectare of triticale shoot biomass.* This definition is necessary since farming inputs are quantified on an area basis, so their energy and environmental impacts need to be quantified this way as well. The impacts on farmland of growing triticale biomass and two other New Zealand-grown feedstocks can be compared in terms of the above FU.

A second FU was required in relation to feedstock supply to a gasification plant. In this case FU = *1.0 tonne dry mass of triticale (contained within biomass of known moisture content, at the farm gate)*. This FU is necessary to consider the impacts per unit of product (in this case per dry tonne of feedstock used for making biofuel).

Another aspect of using this second FU is the need to assess the energy balance in producing triticale biomass from Cradle to Farm Gate. A tonne of dry biomass of different species may contain differing amounts of energy (quantified as Lower Heating Value or Net Calorific Value per tonne dry mass). The crop species also have different yields per ha, which means the impacts per tDM will differ since cropping impacts are quantified on per ha basis. These are considered in the next section.

## Energy Footprint, Energy yield

The energy footprint is the energy consumption of the operations involved in the production of the crop biomass, including energy used for manufactured inputs to the farm. This is actually only one component of the calculations to compare the direct and indirect energy inputs with the energy output stored in the crop biomass, ready for conversion into biofuel and other energy forms. Net energy yield is the bottom line for one set of calculations, but energy ratio is also a very useful indicator of energy balance in the production system.

### Energy consumption

A discussion on the reliability of the energy input values selected for the LCI was made in the companion LCA on giant miscanthus biomass. Where this LCI uses more conservative values compared to overseas literature (higher energy content of diesel fuel and higher per ha rates of fuel use by tractors) there should be no concern that the LCA results are underestimating the energy footprint of triticale biomass cropping in NZ. The studies that do calculate higher energy consumption are usually older and in EU countries, but a comprehensive German manual (Achilles, 1999) on farm statistics and procedures included fuel use and work time per ha and calculated energy values that are consistently lower than used in this LCI for the similar farm procedures.

As detailed in the Energy Balance Results subsection the annual energy consumption to produce triticale biomass in NZ is 15.2 GJ per ha of triticale crop. This equals 0.77 GJ/tDM given the annualised production of 19.8 tDM/ha. The only triticale LCA found in the literature was by Godard et al (2013) in France, who reported a very high energy consumption on an area basis, 13.9 GJ/ha, or 0.99 GJ/tDM on per mass of product basis The higher consumption per tonne in that study was due to lower crop yield (14 tDM/ha) in that climate.

The very clear energy hotspot in this LCA was fertiliser use, especially N fertiliser use. The total fertiliser energy consumption was 11.3 GJ/ha. This represents 75% of the overall energy use; this substantial figure parallels the findings of Godard et al (2013), where fertiliser accounted for 71% of the total.

The only previous analysis of energy use for arable crops in New Zealand was made by Barber (2004). None of the case studies in that analysis was a farm growing whole crop cereal silage, but relevant data could be identified in the analysis. An arable crops farm without irrigation used 12.3 GJ/ha of fertiliser energy. This value and the ratio of fertiliser energy to diesel energy were both quite similar to the triticale LCA, but the total energy consumption for wheat was a third higher at 20.2 GJ/ha. This can partly be attributed to the Barber analysis being on wheat for grain, which requires a few additional operations that are not used to grow whole crop silage (wheat or triticale as biomass). However, the Barber report quantified some energy use aspects that were left out of this study, such as the energy costs of buildings and more tractor implements.

The only other, but secondary, hotspot in this triticale LCA was diesel fuel use at 3.1 GJ/ha. In comparison, the 2004 NZ analysis (Barber) an arable crops farm without irrigation used 3-4 GJ/ha of diesel fuel energy. All other energy inputs in this LCA were quite minor.

Comparison with Jerusalem artichoke and giant miscanthus. Energy consumption for triticale cropping is one and two-thirds times that of JA grown as a perennial for 7 years. The energy footprint of triticale is five and a half times larger than that of Mxg.

## Gross and Net Energy Yields and Energy Ratio

Calculating net energy yield, defined as gross energy yield minus energy consumption, reveals that differences in energy consumption due to differing farming practices or choice of appropriate impact value for each operational input have quite a minor influence on the net energy yield. The total energy consumption was calculated as 15.2 GJ/ha, so the gross energy yield of 338.6 GJ/ha was reduced to a net energy yield of 323.4 GJ/ha. A 30% over- or under-estimate in calculating the energy footprint would give a calculated net energy yield of 323.4 ± 4.56 GJ/ha (or 1% error in net yield). When expressed on a per tDM basis, the net energy yield is 16.3 GJ/tDM. This is also the Lower Heating Value (17.1 GJ/tDM) minus the energy consumption (0.77 GJ/tDM).

### *Gross energy yield*

Reported literature values for gross energy yield of cereals are usually much lower than the value calculated in this triticale LCA. Since the LHV of 17.1 GJ/tDM for wheat (Fehrenbach 2007) is the value used here for triticale, any difference in energy yield ought to be proportional to differences in the DM yield/ha. However, with cereal grains the literature often reports yields and energy content (LHV) values for air dried grain (typically 87%DM), not actual DM. The Barber (2004) report used a USDA reference energy content of wheat as 14.8 GJ/t, which would not have been an oven-dried tonne (100%DM). The calculated gross energy yield is even lower than would be expected on the basis of the DM yield difference.

Triticale's 19.8 tDM/ha is at least three times the non-irrigated wheat biomass yield (calculated as 6.2 t/ha including the straw). But the gross energy yield of 338.6 GJ/ha is 4.5 times the 75.1 GJ/ha calculated from the Barber (2004) analysis.

### *Net energy yield*

Following on from the gross energy yield discussion, the net energy yield and energy ratio results in the NZ study by Barber (2004) are also much lower than this finding for triticale. While the triticale DM yield used in this LCA (19.8 tDM/ha) is much higher than wheat grain + straw yield in that 2004 analysis, it is based on several field measurements of yield that ranged up to 26 tDM/ha. Therefore the energy results calculated from the DM yield can be considered reasonable.

Comparison with giant miscanthus and Jerusalem artichoke. The energy balance for producing the bioenergy crop triticale from the cradle to the farm gate is reasonably favourable, but less so than that of the perennial giant miscanthus. Comparing the gross energy yield is the first step. Mxg gross energy (348.3 GJ/ha-yr) is a little higher than that of triticale (338.6 GJ/ha-yr), due to having higher energy content per tonne (18.22 GJ/tDM versus 17.1 GJ/tDM). This Mxg advantage out-weighs the slightly higher farm gate biomass yield of triticale (19.8 tDM/ha versus 19.3 tDM/ha for Mxg, since Mxg loses DM before it is harvested in winter).

Since the energy inputs for production of Mxg are only 18% of those for triticale it would be expected that Mxg would have a distinctly higher net energy yield. However, the advantage for net energy yield is only 7.7%: 348.3 GJ/ha for Mxg versus 323.4 GJ/ha for triticale. One reason, as explained at the start of this subsection, is that energy consumption is small compared to gross energy yield.

Jerusalem artichoke and triticale are assumed to have the same energy content (LHV), so calculated gross energy yield is proportional to DM yield and therefore greater in JA. JA also had a lower energy consumption per ha than triticale, so the net energy yield (gross – consumption) of triticale is quite a bit lower than for JA (339 versus 442 GJ/ha-yr).

### *Energy ratio*

Perhaps the simplest way to express the energy balance for biomass production is the energy ratio. The ratio for triticale (at the farm gate) between gross energy yield and energy consumption was good (338.6/15.2 = 22:1). Note that this ratio is more sensitive than net energy yield to the size of the energy consumption footprint.

Comparison with wheat. The low energy ratios reported for wheat by Barber (2004) and others result primarily from lower crop yields, but also from higher energy consumption per ha. A triticale biomass crop will use less energy per ha due to fewer energy-using operations to grow it (a smaller denominator in the energy ratio), but the big factor is the larger DM yield which will increase the numerator of the ratio, gross energy yield, proportionally.

Comparison with giant miscanthus and Jerusalem artichoke. It is likely for triticale that an energy ratio of 22:1 is sufficiently positive that it may be feasible to produce biofuel from its biomass and still have a sufficiently positive overall energy balance, making it a relatively successful candidate as a biomass species. It compares less well to the other biomass species assessed in this LCA, however. The energy ratio of Jerusalem artichoke is 35:1 in the planting year, but 52:1 in subsequent years of a perennial plantation. The energy ratio of

Mxg is a highly impressive 129:1. This is based on gross energy yield of 351 GJ/ha-yr and energy consumption of 2.7 GJ/ha-yr.

## GWP footprint

The overall GWP of triticale production in this LCA is 1905 kg $CO_2$e/ha. This is well below the 3,840 kg $CO_2$e/ha reported for by Godard et al (2013), but closer to other overseas findings. One cause of that high value was the use of very high rates of fertiliser (required in the particular soil at the research site in France), but the principal difference may be the way field emissions of $N_2O$ were calculated, which varies considerably among studies.

The most relevant LCA in NZ to compare these results to is the one done for the Foundation for Arable Research (FAR) that included wheat for grain (Barber, 2011). The total GWP calculated in that LCA was 2820 kg $CO_2$e/ha. Whole crop triticale has somewhat lower rates of farming inputs than wheat for grain. Looking at a contribution analysis of the GWP impact factors in the FAR report, it is likely that about 18% of the total is from practices that apply to a grain crop but would not apply to a whole crop for silage or biomass. The total footprint in that study for wheat would be reduced from 2820 to 2310 kg $CO_2$e/ha by subtracting 18%. Some of the remaining difference is that an N fertiliser production impact rate of 4.01 kg $CO_2$/kgN was used in the Barber LCA, citing a 2008 paper. This LCA used a rate from a more recent study by the same NZ researcher (Ledgard et al 2011), which was 1.056 kg $CO_2$/kg urea; this converts to 2.296 kg $CO_2$/kgN. The latest factor reduces by 43% the large 770 kg $CO_2$e/ha N impact on GWP (from using 192 kgN/ha in the wheat analysis) a reduction of 439 kg $CO_2$e/ha.

The N fertiliser rate is also lower in whole crop triticale (150 kgN/ha) or 22% lower, dropping the wheat grain GWP by another 169 kg $CO_2$e/ha. The total GWP of 2310 would therefore be reduced to 1710 kg $CO_2$e/ha, which is lower than the value calculated in this LCA. A side effect of altering the wheat grain contribution analysis in the above manner is that the remaining factors are expanded to larger percentage values. Fertiliser production and soil emissions increase to >75% of total GWP, a very similar contribution as in this triticale LCA.

This comparison provides reasonable confidence that the current LCA has not greatly underestimated the GWP impact of triticale production in NZ.

Comparison with giant miscanthus. While most annual food crops would have similar or higher GWP than the 1905 kg $CO_2$e/ha calculated here, the perennial biomass species, giant miscanthus, has an overall annualised GWP of only 264 kg $CO_2$e/ha (excluding carbon sequestration in the rhizome system). A large part of the difference is from manufacturing fertiliser, used at higher rates for triticale. The 522 kg $CO_2$e/ha (Table 8) is more than 10 times higher than the total fertiliser impact from Mxg cropping miscanthus (with annualised input = 48 kg $CO_2$e/ha). Mxg has a much lower N fertiliser rate and will usually not require lime application.

Since $N_2O$ emissions are also a result of fertiliser use (and urea also causes soil $CO_2$ emissions), the total GWP for all fertiliser use with triticale is 1587 kg $CO_2$e/ha. The total with giant miscanthus is 115 kg $CO_2$e/ha-yr, so triticale impacts are over 13 times greater than those of Mxg.

Comparison with Jerusalem artichoke. First year JA has energy and GWP footprints closer to those of triticale than to Mxg. However, even though annual planting of JA is feasible (while it is not for Mxg), JA is more likely to be grown for 7 or more years as a perennial. The relevant footprints for JA are therefore smaller. GWP is just over half that of triticale.

Therefore, choosing Mxg or JA biomass, rather than triticale or other whole crop cereals, as the feedstock for gasification biofuel would make a greater contribution to climate change mitigation. This advantage of Mxg biomass in terms of GWP occurs despite the energy balance showing that the two species have similar net energy yields. Furthermore, the comparisons do not take into account the large amount of SOC sequestration by an Mxg plantation; the effect on carbon balance may be sufficient to outweigh the entire GWP footprint of Mxg.

## EUT footprint

The overall EUT impact of triticale production is 3.87 kg $PO_4$e/ha. This study focused on diesel fuel impacts on EUT (through $N_2O$ and NOx emissions), which proved to be very small (0.0002 kg $PO_4$e/ha) and impacts on EUT from fertiliser P and N use. Within the fertiliser impacts, loss of N fertiliser $NH_3$ to air (with deposition to lakes and oceans) and direct loss of $PO_4$ to surface waterways from P fertiliser were the major hotspots. The combined N fertiliser emissions made up about two thirds of total impact on EUT, with P fertiliser contributing the other third to EUT.

Reported values of EUT from cereal crop production (when using $PO_4$eq units) are generally higher than calculated in this LCA. One study in France (with EUT units in kg $PO_4$e) found P fertiliser impact for triticale production to have the single largest impact (Godard et al 2013). Supplemental tables in that study gave EUT for triticale as 28 kg $PO_4$e, seven times higher than in this LCA. In contrast, another study in France expressed EUT units in kg Ne/ha rather than $PO_4$e and found that total direct emissions of $NH_3$, $N_2O$ and $NO_3$ were four times higher in EUT impact than N fertiliser production was (Hayer et al 2010) and P fertiliser impact was negligible in the kg Ne/ha units (Hayer et al 2010).

Since EUT impact factors other than fertilisers and diesel fuel were not included in this study, if other LC analyses of biomass crops do identify other factors that greatly increase EUT, then these findings need to be adjusted. If the higher calculated EUT values in the LCA literature are higher largely due to fertiliser and fuel use, but using different methodologies, then the level of uncertainty in EUT calculation makes it difficult to know which methods are more accurate. This LCA used the approach taken by Hamelin et al (2012) (which was selected after an extensive analysis comparing methods in the literature) and it resulted in lower calculated surplus P (and therefore EUT) than in some methods. They concluded for wheat that there was almost no surplus P when a catch crop was grown, while we assumed there was 6 kgP/ha surplus. Therefore our calculated EUT, while low relative to other LCAs, was higher than the value in the study by Hamelin. The study by Hayer et al (2010) also showed a very low contribution by P fertiliser to EUT.

A comparison of the EUT of triticale (3.87 kg $PO_4$e/ha-yr) with EUT of Mxg (0.46 kg $PO_4$e/ha-yr) makes clear the advantage of a perennial species with low N and P fertiliser requirements. The assumptions used to calculate the Mxg EUT during the year of planting and the first part of year 2 (with an exposed soil surface) resulted in calculated EUT those years being similar to the triticale EUT (with emissions to waterways from P fertiliser actually higher for Mxg than triticale). The reason was that Mxg plant uptake of P is so much lower, but the fertiliser applied and soil-incorporated pre-planting needed to suffice for many years, resulting in higher calculated ‘P surplus’ from which EUT is calculated. The low annualised EUT for Mxg is due to no additional P fertiliser application for the remaining 18 years of the plantation life. Much of the EUT value of 0.46 kg $PO_4$e/ha-yr for Mxg could be avoided if a way was found to surface-apply a small amount of P (probably in liquid form) a few times during the 20 years and skip the initial pre-planting application.

## Comparing the three biomass species

Biomass production impacts per tDM varied among the crop species used, as found in this LCA and the other two species LCA reports.  Comparisons related to some practical matters are made in a separate report, which also has tables for energy use, GWP and EUT, each table including all three crop species. An example of a practical difference is that triticale will usually dry to lower moisture content than the other species assessed (15-18%), so the biomass is more amenable to being baled and stored.

## Uncertainties in calculated LC values

Reported LCA studies with field production of biomass (and food) crops reveal a great deal of variability between studies and also uncertainty in the values calculated for impact factors such as GWP and energy consumption.

Differences in literature values can in part be attributed to real differences between crops grown in different climates and soils, using genetically different cultivars. It is also partly due to crop production details reported in crop science papers being used in studies by LCA professionals or economists who lack the specific crop knowledge to apply the details appropriately. The issues with generalised use of the LCI databases, without accounting for influences of the local environment, has been critiqued by Godard et al (2013).

A DISCUSSION section in an LCA should consider whether the methodologies chosen influenced the results. In the author’s view, the choice to develop a new LCI spreadsheet populated with values independently judged most appropriate to use for the New Zealand cropping situation did influence the LCI, for the better. A small number of values related to manufactured equipment or buildings were more efficiently accessed through LCI databases, but other key impacts would have been less accurately calculated by that methodology.

The Mxg LCA report section on uncertainties goes into more detail. It addressed an additional cause of uncertainty: leaving out factors from the LCI for which there is incomplete knowledge, due to the assumption that data from repeat studies will be included when knowledge has improved. That assumption is challenged and the result of the omissions may be a poorer (not better) calculation of impacts, even though uncertainty is reduced.

Regarding the uncertainties that are already recognised in this LCA, the single largest factor is the impact on GWP due to soil emissions of $N_2O$. Which methodology is most accurate is yet to be proven and there are not yet procedures to fine-tune it to a particular cropping site. In the NZ report by Barber (2011a) the issues from using a single emission factor in different farm fields were well summarised: “This report was therefore unable to take into account the effect of nitrogen source and site differences (soil type, rainfall, irrigation, cultivation practice, and residue management) which are likely to affect the level of $N_2O$ emissions.”

A related impact on GWP is the $CO_2$ released from soil organic matter and organisms following cultivation to plant a crop. This factor could be reasonably large, but is omitted by general agreement among the IPCC network, even though for triticale (and probably most annual type crop species) its omission does result in the GWP being underestimated. Other LCI factors omitted in this LCA include indirect energy consumption and GWP inputs for farm buildings and tractor implements.

It remains for future LCA work in biomass crop production to assess how thoroughly triticale production impacts on energy use, GWP and EUT were quantified in this LCA. It may then be able to judge whether adding other aspects have practical significance (i.e. considerable increase the overall footprint of energy use, GWP or EUT) or mainly add completeness by fully conforming to the ILCD methodology guidelines.

In addition to the three impact categories quantified, there are several others that are included in a comprehensive LCA study of a manufactured product but were not included in this study. Energy use, GWP and EUT do not completely represent the impacts of triticale production on the environment. Impact factors that are also important to assess systems that use inputs such as fertiliser, agrichemicals and fuels include: Acidification, Depletion of resources, Ecotoxicity and Ecosystem services impacts (Millennium Ecosystem Assessment, 2005). As the LC Inventory databases reach sufficient levels of certainty these impacts should also be assessed. In the meantime, it would be premature to use this LCA as a basis to refer to triticale biomass production as definitely environmentally beneficial.

## Minimal uncertainties in some key calculated LC values

The Mxg LCA study also discussed those LCI input factors where there is reasonable certainty in the selected values, including use of diesel fuel by tractors and industrial production of fertilisers. The argument in that report is that these impacts, when quantified per ha of biomass production using quite robust calculations, account for a very large portion of the overall GWP and energy consumption.

## Reducing energy consumption; Increasing net energy yield

### Energy consumption

The two obvious contribution factors in triticale production where energy use might be reduced are fertiliser and diesel fuel. The percentage contribution from diesel fuel use in triticale is lower than for fuel use in Mxg production (since triticale energy consumption is more dominated by fertiliser production). However, the annual volume of diesel fuel use for a triticale crop is about double the annualised use in the perennial Mxg. Since production practices for cereal crops in NZ are well established, improving fuel use efficiency with triticale is more challenging than to do so by identifying new (more fuel-efficient) farming practices for a new species like giant miscanthus. Therefore, triticale energy consumption is likely to best be reduced by practices that lower the N fertiliser rate (without too much yield reduction).

### Net energy yield

The choice of triticale as one of the three high potential biomass species to investigate was based in large part on its high DM yield. Gross energy yield in a high-yielding crop is so much greater than energy consumption that a given percentage gain in energy yield has more benefit to net energy yield than the same percentage reduction in energy consumption.

The list of crop species that may outperform triticale will most probably not include many of those having smaller energy and environmental footprints; they will also need to have high DM yields.

### Energy ratio

The energy ratio (Cradle to Farm Gate) calculated in this triticale LCA is good but incomplete. Ultimately, the ratio needs to apply to the whole process, from Cradle to Grave. Such a calculation is likely to be part of a future overall analysis of biofuel production from crop biomass. It seems likely that triticale will have a better overall energy ratio than values published for currently-used biofuel species (oilseed crops and cereal grain seed) used for first generation liquid biofuels. Thorough calculations of these ratios are sometimes <1:1and nearly always <2:1. An example of a careful LCA assessment (Hill et al, 2006) determined the ratio of maize grain ethanol as 1.25:1 and soybean biodiesel as 1.93:1.

In contrast, recent assessments of synthetic diesel from second generation thermochemical technologies have determined their energy ratio to be >4:1 using biomass from woody crops or arable crops grown in the EU where annual DM yields are lower than in this NZ LCA (Sims et al, 2010).

## GWP benefit of fossil fuel substitution with triticale biofuel

Diesel substitution by biofuel in tractors and other engines has considerable potential to reduce the GWP footprint of NZ agriculture and/or NZ transport. The most direct way to measure the benefits of fossil fuel substitution by biodiesel is to determine the GWP footprint of producing and using the biodiesel and subtract that from the GWP footprint from producing and using the fossil diesel it replaces.

This LCA provides the analysis necessary to quantify this benefit from Cradle to Farm Gate. The findings are quantified per ha, but also per dry tonne of biomass, as needed for any future LCA of the GWP footprint of biodiesel production from the farm gate through to fuel use (Farm Gate to Grave).

While the Farm Gate to Grave LCA has not been done in NZ for triticale or the other two biomass species assessed for the BTSL project, an illustration of the overall benefit to GWP footprint was made in the companion report to this one, the Mxg LCA Report. The illustration sourced literature values for biomass to biofuel conversion, using a conservative (high) estimate for GWP of Mxg of about 1 t $CO_2$e/ha of biomass (19.3 tDM). Since triticale crop yield is only slightly higher, the same estimated value as for Mxg (1 t $CO_2$e/ha) can be applied to triticale processing into biofuel. Adding the Cradle to Farm Gate GWP of triticale (1.9 t $CO_2$e/ha) gives an overall GWP of 2.9 t$CO_2$e/ha.

The Mxg LCA Report then equated the fuel yield in the literature, 160 L biodiesel per dry tonne of biomass (Sims et al, 2010), converted to a /ha basis, to the volume of fossil diesel containing the same fuel energy as the biodiesel. For the triticale biomass yield of 19.8 tDM/ha, the calculated volume of fossil diesel the biofuel energy equates with is 2915 L/ha. The GWP footprint just from burning that diesel equals 9.2 t $CO_2$e/ha. This is 85% of the total fossil diesel footprint (McDevitt & Seadon, 2011). The difference, after subtracting the triticale footprint, is about 6 t $CO_2$e/ha, which represents the avoided GWP by biofuel end users, per ha of biomass converted to biofuel. This benefit is equivalent to 2.2 times the estimated full Cradle to Grave GWP footprint for triticale (2.9 t $CO_2$e/ha). This calculated benefit of fuel substitution is quite a bit less than for the two perennial biomass species studied. However, other literature estimates of Farm Gate to Grave GWP are only 20% of the conservative estimate used here, so the benefit to GWP from substituting diesel with biodiesel could be as great as 10 times the JA Cradle to Grave GWP estimated in this illustration.

The Mxg LCA Report also discussed the social and policy dimension of fossil fuel substitution with biofuel. There will be no benefit for climate change if biofuel is used along with all the fossil fuel that would otherwise be used. Policymakers must create disincentives to keep using fossil diesel in order for biofuel use to be truly beneficial. Uncertainty over that occurrence is probably greater than that in these LCA results.

Finally, an important element of the above analysis is the size of the DM yield of the biomass species in question. The biofuel yield and therefore GWP mitigation possible per ha of biomass would have been much lower if the crop yield was only 10-14 tDM/ha, as it is for triticale in northern EU countries and for many other crop species even in the most favourable of climates. This suggests there should be a climatic/geographical component factored in when optimising global bioenergy supply. The NZ yield of triticale biomass is higher than in most other parts of the world, reducing per tDM impacts and raising the potential for mitigation of diesel fuel impacts.

An important element of the above analysis is the DM yield of the biomass species in question. The per ha energy equivalence to fossil diesel would have been much lower if the biomass crop yield was only 8-10 tDM/ha, as it is for many other crops and climates. This factor suggests there should be a climatic/geographical component when optimising global bioenergy supply. The NZ yield of triticale biomass is relatively high compared to other parts of the world, reducing per tDM impacts and raising the potential for mitigation of diesel fuel impacts.

## Data review

Other than the geographical coverage aspect the data review discussion is the same for triticale as for Mxg (see the Miscanthus LCA report).

### Technological Coverage

The data concerning the biomass production process in this study is technologically representative of the unit process studied because it is primary data that relates to the actual operations of the farming system.

### Temporal Coverage

This topic is covered in the Miscanthus report.

### Geographical Coverage

The geographic scope of the study, in terms of field inputs such as crop environmental responses and biomass yield, is quite broad due to the choice of triticale as biomass species. It has been proven to grow successfully in all arable cropping regions of New Zealand.

## General Discussion Topics

### Interfacing the Cradle to Farm Gate LCA with a future Farm Gate to Fuel LCA

The moisture content of baled triticale at the farm gate must be measured to know the yield in tDM (the flow to the second FU, for later use). It will also reveal the tonnage that needs to be trucked to the gasification plant or drying facility, to calculate the efficiency and optimise logistics. This will be a smaller issue for triticale than for Mxg and especially for JA.

### Synchronised biomass supply

Annual variability is to be expected in the in availability of the biomass supply. In order to avoid changes in the supply schedule to the gasification facility careful management to synchronise supply among multiple crop species is necessary. This is addressed for the three biomass species together in a separate report.

### Use of marginal land

This issue is covered in the Miscanthus LCA report.

# CONCLUSIONS

Triticale dry mass yield in New Zealand is very high, 22 tDM/ha at the crop's late summer peak DM, or 19.8 tDM/ha at the farm gate. The NZ climate is very suitable in all traditional arable cropping regions.

These relatively high biomass yields in NZ compared to other parts of the world reduce the environmental impacts per tDM; this enhances the potential for mitigation of diesel fuel impacts on GWP.

The production of the biomass crop triticale has low to moderate energy consumption and environmental impacts per tDM (GWP and EUT): 0.77 GJ for energy consumption, 97 kg $CO_2$e for GWP and 0.20 kg $PO_4$e for EUT. In comparison to the other two biomass species assessed (JA or Mxg), these impacts are higher than for either. However, the JA values exclude the impacts of off-farm drying of the JA biomass to 18% moisture, needed in order to store it in bales like triticale or Mxg.

The major hotspots for energy consumption were N fertiliser manufacture and diesel fuel use in tractors; the main hotspot for GWP was N fertiliser soil emissions, followed by N fertiliser manufacture and diesel fuel use; the hotspot for EUT was N and P fertiliser use.

The net energy yield from producing the bioenergy crop triticale from the cradle to the farm gate is quite high (323 GJ/ha-yr), but still the lowest of the three species assessed due to the lower DM yield than JA and lower energy content than Mxg.

The triticale energy ratio between gross yield and energy consumption is 22:1. This is lower than the ratio for a perennial JA plantation (50:1) and much lower than that of the perennial species Mxg (129:1). The very small energy footprint is the basis of the exceptionally high energy ratio for Mxg.

The above conclusions need to be considered in the context of stringent professional LCA standards. System boundary issues do not appear to be major but underlying assumptions about some data sets are not known. Triticale is in commercial production in NZ, but not often as whole crop silage. The analysis was made using specialist-recommended input rates, not real world data sets from farm operations as in the LCA on arable crops by Barber (2011a).

## TRITICALE RECOMMENDATIONS

To reduce both GWP and energy impacts of triticale production the main focus should be on maximising N fertiliser use efficiency.

While it adds cost, switching from urea-N to other N fertilisers is part of ‘best practice’ in terms of minimising GWP. This avoids 238 kg $CO_2$/ha emissions from soil (12% of the total GWP) which occurs following urea use at a rate of 150 kgN/ha.

The reduction in energy footprint by reducing fuel may be possible, but a much larger benefit (perhaps equal to eliminating a large part of the fuel footprint of JA biomass production) is to use biodiesel in tractors instead of fossil diesel.

To reduce transport volume, maximise bale compaction by using the right bale size and type of equipment.

As baled triticale may be drier than baled Mxg it may be the best choice for long-term storage. That would make it pay to use good quality tarpaulins over the stack.

For additional operational recommendations see the Triticale Protocol report.

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# APPENDICES

## Appendix A. Operational Calculation Spreadsheet

Populating the Excel™ calculation spreadsheet with appropriate values constituted the principle task of the LCI process. The three main calculations from the spreadsheet are Energy consumption (GJ/ha) and the two environmental impacts Global Warming Potential (GWP100 as $CO_2$e/ha) and Eutrophication (EUT100 as $PO_4$e/ha), both on a 100 year basis. The values are first calculated on a standardised basis, either per kg of fertiliser used or per hectare of cropped Triticale in a single year.

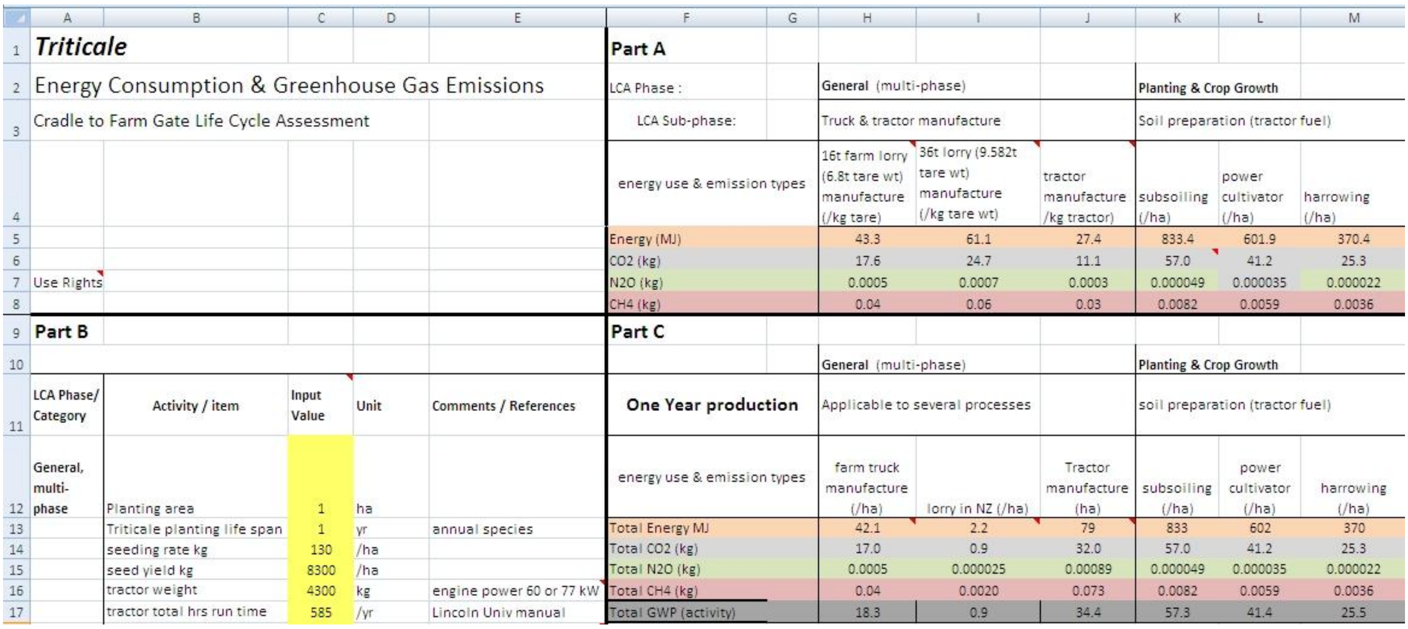
The spreadsheet is organised in three sections. Part A includes all the operations involved in production of triticale biomass, set out across the top of the spreadsheet in columns. The operations are located to follow the production sequence, enabling data to be reported clearly in the order of unit processes in the supply chain from cradle to farm gate. There are four rows of values calculated in Part A: Energy (MJ), $CO_2$, $N_2O$ and $CH_4$ emissions. These calculations make use of Part B values.

Part B is a long list of input values that are either engineering constants or selected values of variables based on NZ experience or chosen from among literature values used for LCA of triticale or related crop species. These are all in column C of the spreadsheet, with their name in column B, units in column D and notes on their source in column E. Part B values are used in formulas for both Part A and Part C.

Part C is the spreadsheet detailed results section, with the values for inputs for 1ha triticale production. Each of these calculations started with the corresponding cell value in Part A, modified by values from Part B to generate the total annual inputs/ha values, including the fertilisers that are on a per kg basis in Part A. There are four rows of values that correspond to the four rows in Part A, each cell in Part A being converted into the per year totals of Part C. The fifth row calculates GWP100 from the three greenhouse gas values in each column.

Figure A1 is an image of the upper left corner of the Operations Calculation Sheet, with a few columns of Part A in the upper right (with Part C underneath) and a few rows of Part B on the left. Part A shows the rate of energy use or emissions of GHG across the top of the spreadsheet in 38 columns, grouped under three phases: 1) Planting & Crop Growth; 2) Harvest & Handling; and 3) Storage. Part C looks similar, but shows the total impact for each operation, usually on per ha basis.

Part B of the Operations Calculation Spreadsheet contains a long list of input values that are either engineering constants or selected values of variables assessed in part on how well they fit the real data from the 3-year NZ field trials. Some of these values are illustrated in Tables 1, 2 and 3 (in the main report above, so not repeated here). For more detailed explanation of the items in the tables see the Mxg LCA Report, Appendix A.



| | A | B | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | ***Triticale*** | | | | | **Part A** | | | | | | | |
| 2 | Energy Consumption & Greenhouse Gas Emissions | | | | | LCA Phase : | | **General** (multi-phase) | | | **Planting & Crop Growth** | | |
| 3 | Cradle to Farm Gate Life Cycle Assessment | | | | | LCA Sub-phase: | | Truck & tractor manufacture | | | Soil preparation (tractor fuel) | | |
| 4 | | | | | | energy use & emission types | | 16t farm lorry (6.8t tare wt) manufacture (/kg tare) | 36t lorry (9.582t tare wt) manufacture (/kg tare wt) | tractor manufacture /kg tractor) | subsoiling (/ha) | power cultivator (/ha) | harrowing (/ha) |
| 5 | | | | | | Energy (MJ) | | 43.3 | 61.1 | 27.4 | 833.4 | 601.9 | 370.4 |
| 6 | | | | | | CO2 (kg) | | 17.6 | 24.7 | 11.1 | 57.0 | 41.2 | 25.3 |
| 7 | Use Rights | | | | | N2O (kg) | | 0.0005 | 0.0007 | 0.0003 | 0.000049 | 0.000035 | 0.000022 |
| 8 | | | | | | CH4 (kg) | | 0.04 | 0.06 | 0.03 | 0.0082 | 0.0059 | 0.0036 |
| 9 | **Part B** | | | | | **Part C** | | | | | | | |
| 10 | | | | | | | | **General** (multi-phase) | | | **Planting & Crop Growth** | | |
| 11 | **LCA Phase/ Category** | **Activity / item** | **Input Value** | **Unit** | **Comments / References** | **One Year production** | | Applicable to several processes | | | soil preparation (tractor fuel) | | |
| 12 | **General, multi-phase** | Planting area | 1 | ha | | energy use & emission types | | farm truck manufacture (/ha) | lorry in NZ (/ha) | Tractor manufacture (ha) | subsoiling (/ha) | power cultivator (/ha) | harrowing (/ha) |
| 13 | | Triticale planting life span | 1 | yr | annual species | Total Energy MJ | | 42.1 | 2.2 | 79 | 833 | 602 | 370 |
| 14 | | seeding rate kg | 130 | /ha | | Total CO2 (kg) | | 17.0 | 0.9 | 32.0 | 57.0 | 41.2 | 25.3 |
| 15 | | seed yield kg | 8300 | /ha | | Total N2O (kg) | | 0.0005 | 0.000025 | 0.00089 | 0.000049 | 0.000035 | 0.000022 |
| 16 | | tractor weight | 4300 | kg | engine power 60 or 77 kW | Total CH4 (kg) | | 0.04 | 0.0020 | 0.073 | 0.0082 | 0.0059 | 0.0036 |
| 17 | | tractor total hrs run time | 585 | /yr | Lincoln Univ manual | Total GWP (activity) | | 18.3 | 0.9 | 34.4 | 57.3 | 41.4 | 25.5 |

**Figure A1. Partial screen view of Triticale Operations Calculation Sheet showing input values (A), constants and conversions (B) and outputs for the LCI (C).**

## Input Values for Part A of Operational Calculation Spreadsheet

To calculate values to use for Part A diesel fuel energy was straightforward for energy input, since a single value (in MJ/L of diesel) was used throughout. The choice of appropriate value is described in Appendix B. GWP calculation, however, required formulas that used constituent values taken from the literature (however, these differed between papers, giving a range of values to select from and justify).

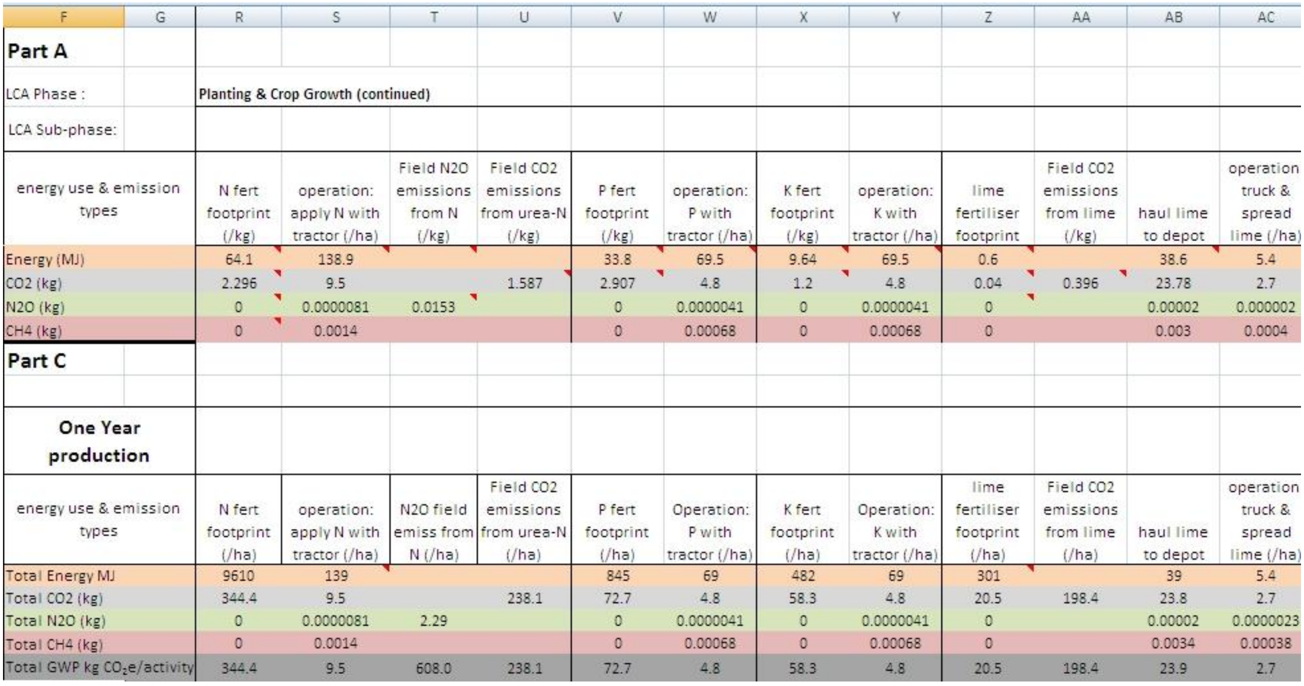
With few exceptions, values from Part B were used in the formulas to calculate the value in each cell of Part A. For values that are exceptions the source of the chosen value is named in an inserted Comment in the Calculation sheet.

The values in Part A are presented in terms of the most relevant denominator (shown in the Fig A1 column heading), for example per hectare for a tractor operation or per kg of nutrient for the impact of using a fertiliser. The three rows for GHG values are stated in units of kg GHG/kg nutrient in the fertiliser columns, but as kg GHG/ha for fossil fuel use. The GHG emissions per ha is calculated from fuel use volumes/ha in Part B, avoiding the confusion that it may cause to express GHG from diesel as kg/L, since much of the GWP literature gives GHG from diesel as kg/kg.

The several operations required for biomass production were grouped under four phases: 1) Planting & Crop Growth; 2) Harvesting & Handling; and 3) Storage. There was also a “Machinery manufacture” category for inputs that applied across phases, such as the embodied energy and footprint from manufacturing a tractor. These phases were oriented across rows in the spreadsheet in Part A. There were 4 rows, one for energy input (in MJ) and three for the greenhouse gases that contribute most to GWP from use of fuels: carbon dioxide (CO2), nitrous oxide or dinitrogen oxide (N2O) and methane (CH4).

The Phase 1 section of Part A, Planting & Crop Growth, is illustrated in Table A-1. There is a sub-phase called Soil preparation, including three operations. These are subsoiling, heavy cultivation, and light cultivation (the latter two both done with a power harrow). The values in the four rows under each column are the direct energy consumption and GHG emissions for tractor use of diesel fuel. The energy use for an operation was calculated based on the volume (rather than weight) of fuel required to apply each operation to a land area of 1.0 ha, since the references on fuel use in farming are all based on L/ha (or gal/ac in the USA). The volume (from Part B) was multiplied by a standard value of energy use associated with use of 1 L of diesel fuel. Since diesel is derived from oil and oil energy content varies, as well as refining process, there are many values in use by engineers. See Appendix B for an explanation of the choice of the value 46.3 MJ/L in this LCI. Fertiliser details are shown in Fig. A2.

**Figure A2. An image from Parts A and C of the Triticale Operations Calculation Sheet. Part C show the calculated values for energy use (top row of the lower band) and GWP emissions (bottom shaded row) from each fertiliser operation.**



| F | G | R | S | T | U | V | W | X | Y | Z | AA | AB | AC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Part A** | | | | | | | | | | | | | |
| LCA Phase : | | Planting & Crop Growth (continued) | | | | | | | | | | | |
| LCA Sub-phase: | | | | | | | | | | | | | |
| energy use & emission types | | N fert footprint (/kg) | operation: apply N with tractor (/ha) | Field N2O emissions from N (/kg) | Field CO2 emissions from urea-N (/kg) | P fert footprint (/kg) | operation: P with tractor (/ha) | K fert footprint (/kg) | operation: K with tractor (/ha) | lime fertiliser footprint | Field CO2 emissions from lime (/kg) | haul lime to depot | operation truck & spread lime (/ha) |
| Energy (MJ) | | 64.1 | 138.9 | | | 33.8 | 69.5 | 9.64 | 69.5 | 0.6 | | 38.6 | 5.4 |
| CO2 (kg) | | 2.296 | 9.5 | | 1.587 | 2.907 | 4.8 | 1.2 | 4.8 | 0.04 | 0.396 | 23.78 | 2.7 |
| N2O (kg) | | 0 | 0.0000081 | 0.0153 | | 0 | 0.0000041 | 0 | 0.0000041 | 0 | | 0.00002 | 0.000002 |
| CH4 (kg) | | 0 | 0.0014 | | | 0 | 0.00068 | 0 | 0.00068 | 0 | | 0.003 | 0.0004 |
| **Part C** | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| **One Year production** | | | | | | | | | | | | | |
| energy use & emission types | | N fert footprint (/ha) | operation: apply N with tractor (/ha) | N2O field emiss from N (/ha) | Field CO2 emissions from urea-N (/ha) | P fert footprint (/ha) | Operation: P with tractor (/ha) | K fert footprint (/ha) | Operation: K with tractor (/ha) | lime fertiliser footprint (/ha) | Field CO2 emissions from lime (/ha) | haul lime to depot | operation truck & spread lime (/ha) |
| Total Energy MJ | | 9610 | 139 | | | 845 | 69 | 482 | 69 | 301 | | 39 | 5.4 |
| Total CO2 (kg) | | 344.4 | 9.5 | | 238.1 | 72.7 | 4.8 | 58.3 | 4.8 | 20.5 | 198.4 | 23.8 | 2.7 |
| Total N2O (kg) | | 0 | 0.0000081 | 2.29 | | 0 | 0.0000041 | 0 | 0.0000041 | 0 | | 0.00002 | 0.0000023 |
| Total CH4 (kg) | | 0 | 0.0014 | | | 0 | 0.00068 | 0 | 0.00068 | 0 | | 0.0034 | 0.00038 |
| Total GWP kg $CO_2$e/activity | | 344.4 | 9.5 | 608.0 | 238.1 | 72.7 | 4.8 | 58.3 | 4.8 | 20.5 | 198.4 | 23.9 | 2.7 |

The other sub-phases of Planting & Crop Growth are Planting, Fertiliser use, Seed treatment, Insect control, Disease control and Weed control. Each sub-phase has multiple operations, such as those for Fertiliser use. It contains sets of columns for the 3 macronutrients nitrogen, phosphorus, and potassium (NPK) plus lime. Each set has a column for the footprint (embodied energy and GWP) and one for tractor fuel use to apply it. For N fertiliser there is an additional column to calculate soil emissions of the potent GHG, $N_2O$.

Phase 2 is called Harvest & Handling. Its sub-phases are Mow, Bale, Haul bales (to the on-farm storage site), and Stack bales. The inputs for these are tractor fuel consumption (plus the indirect energy and GWP effects embodied in the tractor and implements).

Phase 3 in Part A is Storage, which involves the sub-phases Unstack & load bales (at the farm gate) and Storage impacts. The impacts are from manufacture of the reusable tarpaulins for deflecting rain from the stacked bales, since storage buildings are not required in the NZ climate.

A separate spreadsheet was used to calculate EUT. The calculation was only applied to the overall inputs for N fertiliser and P fertiliser and not to each cropping operation along the way. The methodology was described in the main report above.

### Input Values for Part B of Operational Calculation Spreadsheet

The constant for diesel energy content mentioned in Part A was one of the >90 Part B values in column C (see Table 3 in the main report). They are input values that are either defined constants or the value of variables applied to this planting of the biomass crop Triticale. The physical/engineering constants only needed to be searched in the literature. The variable inputs, such as rate and frequency of fertiliser to apply, required a study of the relevant literature on Triticale and other species. The findings were assessed in part on how well they fit the observations from the 3-year NZ field trials. The main inputs in this regard are the use rates for fertiliser and herbicides, crop yields and biomass energy content.

Values in Part B also include the following: inputs for embodied energy in farm equipment (to manufacture, ship to NZ and maintain), tractor fuel use differences by operation, numbers of times operations were repeated, literature values for impacts of fertiliser and herbicide production, IPCC values for the relative impact on GWP of the relevant GHGs, and the energy content in the biomass produced. The last value is used to calculate the gross energy yield in relation to energy consumption, giving the net energy yield.

### Output Values in Part C of Operational Calculation Sheet

Part C is the spreadsheet results section. Each of these calculations started with the corresponding cell value in Part A, modified by values from Part B to generate the (and values over the full season on per ha basis.

The operation calculation spreadsheet also has a series of Summary Tables which total the energy use and GHG emissions for all phases of Triticale cropping (plus a GWP column that combines the three GHG emissions values into a single $CO_2$ equivalent value). These are presented in the RESULTS section of the main LCA report, along with a summary of the above Appendix A details.

In addition to the Operations Calculation Sheet and the Summary Tables, the Excel file these are contained in has three sheets used to list and calculate the values that are utilised in Part B of the Op Calc Sheet. These are: Agricultural Operations, Physical Constants and Machinery & Diesel Fuel Physical Constants.

## Appendix A2. Eutrophication Calculation Sheet

The second category of environmental impact in this study is Eutrophication (EUT). Due to the scarcity of data it was decided to limit the analysis to the emissions from the diesel fuel burnt in tractors during the life cycle of the crop as well as the EUT-related emissions from fertilisers use and manufacture. The calculations for impacts from giant miscanthus operations were made in a separate spreadsheet in the same file as the energy use and GWP calculations (partially shown here).

### *EUT from N emissions*

There are four forms of N that impact on the eutrophication footprint. One gas, $N_2O$ is both emitted into air (and lands in water) from fuel use and is produced in soil air using fertiliser N.

**Table A2-1. Four emission types (forms of N) and the Mxg production operations that are the source of each N emission type. Many environmental features contribute to the values that have been determined as characterisation factors.**

| Emission type | Source of emissions | CML Characterisation Factors (1kg = 0.xx kg $PO_4$) |
|---|---|---|
| $N_2O$ | Both fuel & fert. use | 0.27 |
| NOx | Fuel use | 0.13 |
| NH3 Ammonia | Fertiliser use | 0.35 |
| NO3 Nitrate (surplus) | Fertiliser use | 0.1 |

Characterisation Factors have been developed for emissions that cause EUT. The step before applying each of these Factors is to quantify each type of N emissions from the N fertiliser (or tractor fuel) used to produce Mxg biomass. The calculations by several research studies have yielded a range of values. For Mxg the low end of each range would be a reasonable choice for the N emissions of each type. Tables A5 and A6 present the relevant factors for N eutrophication calculation.

**Table A2-2. Referenced emission ratios to quantify N emissions of each type.**

| N Emission type/source | Direct emission ratios | Indirect emission ratios |
|---|---|---|
| $N_2O$ kg/kg diesel | 0.000003 | unknown |
| $N_2O$ as % of N fert. | 1.5% | 1.5% of N surplus (leached NO3-) |
| $NO_x$ as % of N inputs | 0.6% | +1% of volatized $NO_x$ (Bessou) |
| $NH_3$ as % of N inputs | 2.6% | +1% of volatized NH3 (Bessou) |
| $NO_3^-$ as % of N surplus | 1.0% | unknown |

### *EUT from P emissions*

Leaching of P is lower than nutrient N due to its low solubility and strong adherence to soil surfaces. For P from fertiliser in arable crops where mineral P is incorporated in the soil there is very little leaching to groundwater or runoff to waterways. Soil erosion, however, allows the attached P to be carried to waterways. P loss rate is a subject of complex research, with many methods being attempted to quantify it. Hamelin et al (2012) in Denmark assessed several diverse methods and concluded that most results were in line with the simple calculation of losses for annual type crop species as 5% of the net surplus of applied P fertiliser (mineral or manure slurry). For perennial species P loss was calculated as 2.5% of the net surplus of P. In the Mxg EUT calculation sheet we assumed fertiliser P was applied at a rate of 25 kg/ha to supply the plantation for its 20-year lifespan. Since the soil under a new Mxg crop is exposed like in an annual crop The P loss to contribute to EUT was calculated by assuming 5% of the surplus P was lost in year 1 and 2.5% was lost in the next two years before a full canopy was in place. The Table A6 CLM factor is for the contributing forms of P involved in crop production, expressed as $PO_4$.

**Table A6. The CML Characterisation Factor applied to surplus P (after plant uptake) from applied fertiliser.**

| Emission to water | Source of emissions | CML Characterisation Factor (1kg =0. xx kg $PO_4$) |
|---|---|---|
| P (surplus) | Fertiliser | 3.06 |

## Appendix B. Diesel energy value calculation.

Since diesel is derived from petroleum and its energy content varies in different sources of petroleum, as well as due to refining processes, there are many values in use by engineers. In this analysis the value used was based on the International Energy Agency definition of the energy content of 1.0 tonne of oil equivalent (toe) as 10.0 kcal or 41.868 GJ/tonne. This is called the Lower Heating Value (LVH) and is also called the Net Calorific Value. It can be expressed on either a mass basis as above or can be converted to a volume basis using the IEA value for oil density (0.853 kg/L). The volume basis value by the above calculation is 35.67 MJ/L. This value would be an acceptable choice to use as the energy content at the point of consumption anywhere that a locally-developed value is unavailable, but it should be noted that it does not include the ‘fugitive’ primary energy expended before the diesel fuel reaches the consumer.

In New Zealand some fuel is refined in the country and some is imported. The Ministry for Economic Development has calculated the energy content of diesel at the point of consumption as 38.4 MJ/L, on a volume basis as used in most consumer data, such as L/hr or L/ha of diesel fuel use by tractors. Primary energy use per L of diesel requires adding the additional sources of ‘fugitive’ energy (diesel, other fossil fuels and electricity) required before the fuel reaches the consumer. Barber (2011) has calculated these to add 0.207 MJ per MJ at the consumer. Using the factor of 1.207, the MED value for consumer energy (38.4 MJ/L) becomes **46.3 MJ/L**.

### Diesel References

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